Alain Bernard *Editor*

Global Product Development

Proceedings of the 20th CIRP Design Conference, Ecole Centrale de Nantes, Nantes, France, 19th–21st April 2010

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Preface

The CIRP Design 2010 Conference has been very productive on the scientific point of view, despite “the cloud” from the volcano in Island, and all the negative consequences on attendance.

But fortunately, electronic communications allow the speakers who had transportation difficulties to present their contributions through videoconferencing system.

The CIRP Design Conference is an official conference from the CIRP (International Academy for Production Engineering), this was the 20th issue of this event.

This book has been built from the different papers presented during the keynote sessions and the parallel sessions.

The different sessions of the CIRP Design 2010 Conference were constituted with papers that relate to the actual topics concerning design and mainly on the Global Product Development point of view. This proceedings book gives a very relevant and representative view of the actual trends in Design. Its organisation is based on the different topics that have been addressed during the conference.

As the Global Product Development topic is very important for academic structures, industrial companies and more generally, the civil society, it is important to underline the fact that many sponsors have decided to support this event. We kindly thank all of them for their support.

We also thank the honorary President, Prof. Michel Véron, former President of the CIRP, all the scientific committee members for their active and very important contribution to the scientific quality of this event, and the organisation committee for the hard work during the preparation and the execution of this event. . . mostly because of “the cloud”. . .

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Value, Risk and Cost Management in Global Product Development

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Keynotes on General Trends in Global Product Developments

Design of On-Line Electric Vehicle (OLEV)

N.P. Suh, D.H. Cho, and C.T. Rim

Abstract To minimize the greenhouse effect caused by emission of CO_2, many automobile manufacturers are developing battery-powered automobiles that typically use re-chargeable lithium polymer (or ion) batteries. However, the future of these battery-powered electric cars is less than certain. The re-chargeable lithium batteries are heavy and expensive with a limited life. Furthermore, Earth has only about 10 million tons of lithium, enough to put one battery system in each vehicle in use today worldwide. This chapter presents a new design concept for an alternate electric car – On-Line Electric Vehicle (OLEV). OLEV draws its electric power from underground electric coils without using any mechanical contact. The maximim efficiency of power transmission over a distance of 17 cm is 72%. OLEV has a small battery, which enables the vehicle to travel on roads without the underground electric coil. Batteries are recharged whenever OLEV draws electric power from the underground coils and thus, do not require expensive separate charging stations. The infrastructure cost of installing and maintaining OLEV is less than those required for other versions of electric vehicles. This chapter presents the overall design concept of OLEV.

Keywords Axiomatic design · Electric car · Wireless power transmission · Automobile · System design

1 Introduction

This paper[1] presents the overall design concept of a new electric vehicle being developed at KAIST.[2] The all-electric car of KAIST, named the On-Line Electric Vehicle (OLEV), acquires the electricity from underground coils via wireless transmission of electric power. This innovative technology addresses three major problems: Korea's energy infrastructure that depends on imported petroleum, the poor quality of air in large cities, and the global warming caused by greenhouse gases.

According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the ambient temperature of the earth may rise by more than 2°C relative to the pre-industrial level unless the average CO_2 concentration of the earth's atmosphere is reduced by 50% and that of the industrialized nations by close to 100% [1]. If the temperature rise is unchecked, we may invite many adverse ecological consequences such as heat waves, drought, tropical cyclones, and extreme tides. To prevent such ecological calamity, many nations are now imposing limits on greenhouse gas emission.

Historically major new technological advances have become the engine for economic growth. With economic growth, the use of energy has also increased. Since the primary source of energy has been fossil fuels, the concentration of greenhouse gases in the atmosphere, especially CO_2, has increased. Today, the United States and China are two of the major emitters of CO_2 on per capita basis, while on GDP basis, Russia and China are the leading CO_2 generators. International Energy Agency [2] clearly states that the current energy trend is not sustainable environmentally, economically and socially. Therefore, we must devise solutions to achieve the future economic growth without adverse environmental effects.

There are some 800 million automobiles with internal combustion (IC) engines in use today worldwide. These automobiles are a major source of greenhouse gases, especially CO_2. Thus, an effective way of dealing with the global warming problem is to replace IC engine-powered automobiles with all electric vehicles. The use of electric cars will also improve the quality of air around major cities.

To replace IC engines, many automobile companies are developing "plug-in" electric cars, which use lithium ion (or polymer) batteries that can be recharged at home or at

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[2] Acronym for Korea Advanced Institute of Science and Technology.

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charging stations. However, the basic premise for plug-in electric cars raises many questions. First, the cost of lithium batteries is high. Second, the batteries are heavy. Third, the charging time for the battery is so long that it requires an expensive infrastructure for charging stations. Finally, perhaps the most important of all, is the finite supply of lithium on Earth. Earth has only about ten million tons of lithium that can be mined economically, which is enough for about 800 million cars, almost the same as the number of cars in use today.

The KAIST On-Line Electric Vehicle (OLEV[3]) draws its electric power from underground coils without any mechanical contact [3]. OLEV cars and buses have a small auxiliary battery to propel the vehicle on roads without the underground coil. The battery is also used when extra power is needed. In 2009, we installed underground coil systems on the KAIST campus and built an OLEV bus and an OLEV SUV, which are used for design verification. The maximum efficiency of electric power transfer of the OLEV systems is 72%. We are planning to install an experimental bus line in Seoul, the capital city of Korea in 2009, and other cities in 2010.

This paper describes the overall concept of the OLEV system. The details of the design will appear in future publications.

2 Functional Requirements (FRs) and Design Parameters (DPs) of the On-Line Electric Vehicle (OLEV)

2.1 FRs, DPs, and Constraints of OLEV

The performance of OLEV is expected to be approximately the same as vehicles with IC engines. The highest-level functional requirements (FRs) of OLEV are as follows [4, 5]:

FR1 = Propel the vehicle with electric power
FR2 = Transfer electricity from underground electric cable to the vehicle
FR3 = Steer the vehicle
FR4 = Brake the vehicle
FR5 = Reverse the direction of motion
FR6 = Change the vehicle speed
FR7 = Provide the electric power when there is no external electric power supply
FR8 = Supply electric power to the underground cable

[3] Patents pending. Trade mark OLEV is also pending.

Constraints are as follows:

C1 = Safety regulations governing electric systems
C2 = Price of OLEV (should be competitive with cars with IC engines)
C3 = No emission of greenhouse gases
C4 = Long-term durability and reliability of the system
C5 = Vehicle regulations for space clearance between the road and the bottom of the vehicle

The design parameters (DPs) of OLEV may be chosen as follows:

DP1 = Electric motor
DP2 = Underground coil
DP3 = Conventional steering system
DP4 = Conventional braking system
DP5 = Electric polarity
DP6 = Motor drive
DP7 = Re-chargeable battery
DP8 = Electric power supply system

2.2 The Second Level FRs, and DPs

The first-level FRs and DPs given in the preceding section must be decomposed until the design is completed with all the details required for full implementation.

The second-level FRs are the FRs for the highest-level DPs and at the same time, the children FRs of the first-level FRs [4, 5]. For example, FR1 can be decomposed to lower-level FRs, e.g., FR11, FR12, etc, which are FRs for DP1. Then DP11 can be selected to satisfy FR11, etc. These lower-level FRs and DPs provide further details of the design. There are many patents pending, which describe the details of the OLEV system, including the lower-level FRs and DPs [3].

2.3 Design Matrix (DM)

Design Matrix (DM) relates the FR vector, {FRs}, to the DP vector, {DPs}, which can be formulated after DPs are selected to satisfy the FRs. DM is used to check if there is any coupling of FRs caused by the specific DPs selected for the design. According to the Independence Axiom, FRs must be independent of each other.

An integration team of the OLEV project constructed the DM for the OLEV system to identify and eliminate coupling between the FRs at several levels. The final design was either uncoupled or decoupled designs. When there was coupling, its effect was minimized by making the magnitude of the element of the design matrix that caused coupling much smaller than other elements through design changes.

2.4 Modelling of the FRs and DPs

A given FR may have several different DPs. In this case, the final DPs were selected through modelling and simulation of the design using different DPs. The final values of DPs were also determined through modelling and simulations before the hardware was actually built.

3 Physical Embodiment

3.1 OLEV Bus

Figure 1 shows the OLEV bus built on the KAIST campus. KAIST and collaborating industrial firms converted a conventional bus with an IC engine to an OLEV bus. We attached power-receiving units to the bottom of the bus, which picked up the power transmitted from the underground coil. The distance between the underground coil and the power-receiving unit on the bus was about 17 cm. The maximum electric power transfer efficiency was 72%, which exceeded our design goal of 60% (See Fig. 2). With the reduction of the distance between the pick-up unit and the underground coil, the efficiency increases.

The OLEV bus is designed to draw 60 kW of electric power. When it needs more power for acceleration, etc., it draws additional power from the battery, which is recharged when the motor does not need the peak power.

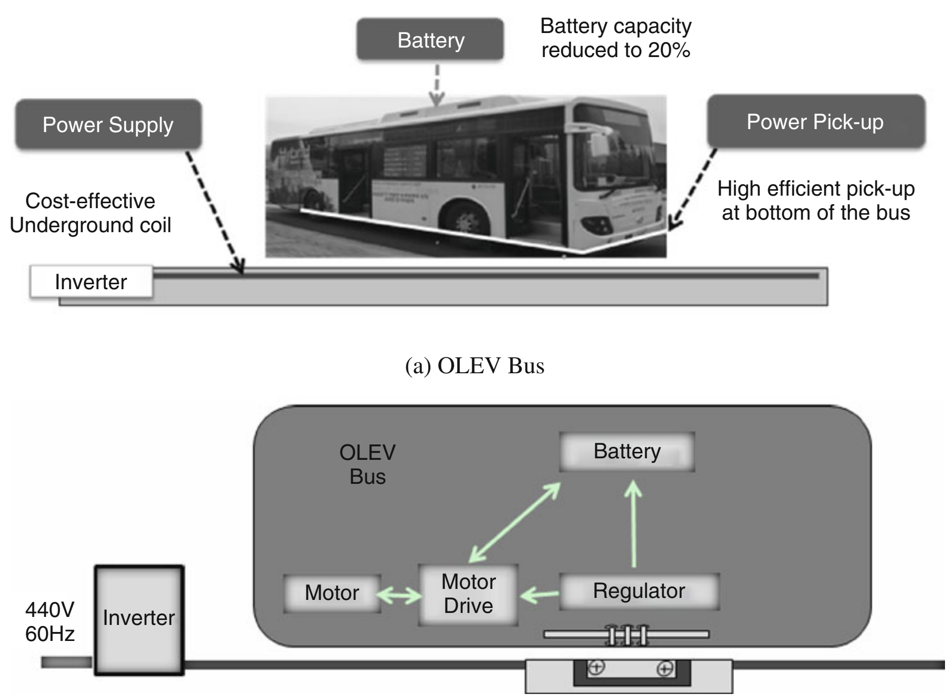
3.2 Underground Electric Coil

The design of the underground coils is one of the most important parts of the OLEV system. We have designed many different versions.

The underground electric power coils do not need to be installed everywhere because the small battery on board can supply the power when the electric power from the underground coil is unavailable. The distance the vehicle has to travel without getting the power from the underground coil determines the battery size. Our current design goal is to install a battery that can give free driving ranges of 10 km for a bus and 30 km for a car.

According to our analysis, if about 30% of the roads in Seoul have the underground electric power coil, most vehicles will be able to drive around the city without recharging the battery off-line.

In the case of OLEV buses that follow pre-determined routes, the underground electric power line will be installed at the bus stations, intersections with stoplights, and only



(a) OLEV Bus

(b) Block diagram of OLEV

Fig. 1 OLEV bus and block diagram. (**a**) OLEV bus and (**b**) Block diagram of OLEV

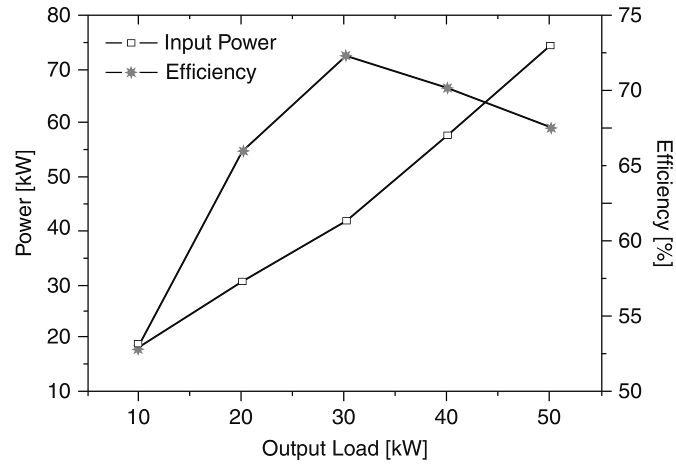


Fig. 2 The power and efficiency of the OLEV

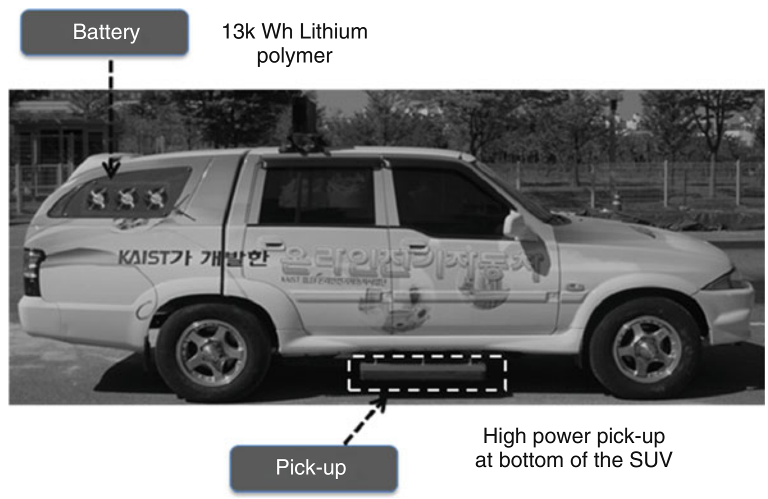


Fig. 3 High powered OLEV SUV

critical segments of the road. While the bus is at a station to discharge passengers and pick up new passengers, the battery is recharged so that the OLEV bus can reach the next bus station with the battery power.

3.3 OLEV SUV

We also built an OLEV sports utility vehicle (SUV). It also had a power pick-up unit attached to the bottom of the vehicle and a set of batteries for free travel when the underground power line is absent. The OLEV SUV is designed to draw about 20 kW of power. (See Fig. 3).

3.4 Cost of the OLEV System

We compared the infrastructure cost of OLEV versus many other electric vehicle systems, which is shown in Fig. 4. The infrastructure cost of OLEV is only about 73% of that of

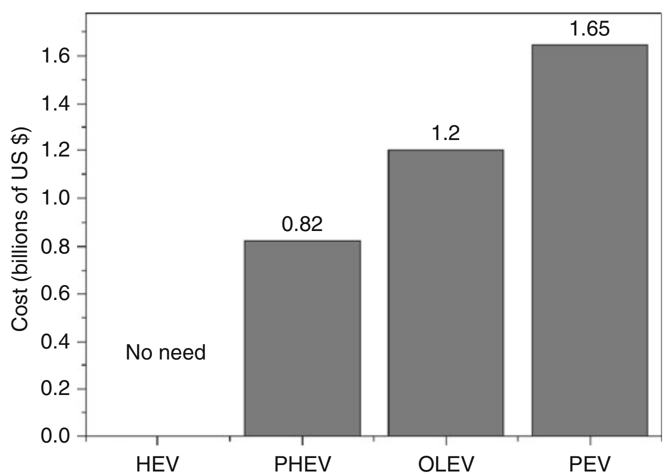


Fig. 4 Comparison of the cost for infrastructure for PEV (plug-in all battery electric vehicle), OLEV, PHEV (plug-in hybrid electric vehicle), and HEV (hybrid electric vehicle with IC engine). Assumtion: The infrastructure is constructed in Seoul, Korea

Table 1 Energy consumption costs (Driving distance: 13,286 km per year)

Type	Energy consumption per year Gasoline (L)	LPG (L)	Electric (kWh)	Total energy cost ($/year)	Reduced energy cost ($/year)
Gasoline	874			1,254	–
OLEV			4,429	391	863
HEV	624			895	360
HEV (LPG)		746		639	616
PHEV	312		1,536	568	686
PEV			3,126	276	979

all battery driven systems. Its cost also compares favourably with electric track-trolley system by a greater margin.

As shown in Table 1, the operating cost of OLEV, which is primarily the electricity cost, is estimated to be only 31% of cars that use gasoline.

The manufacturing cost of OLEV passenger vehicles should be less than that of the hybrid cars and even regular cars with IC engines when they are produced in economical lot sizes.

3.5 Electromagnetic Field (EMF)

Whenever electrical devices are used, including coffee maker at home, electromagnetic fields are emitted. The allowable level of EMF depends on the frequency of the electromagnetic field.

We have made extensive measurements of the electromagnetic field, including the regions around the underground power line, between the OLEV vehicle and the underground power lines, and inside the vehicle.

Near the platform where passengers wait for the OLEV, it is in the range of a few tens of mG, which is well within the allowable limit. Inside the OLEV bus, the EMF level is negligible, being in the range of 1–20 mG depending on the position. Between the area right below the vehicle and the road, which is not accessible to passengers, the EMF level may exceed the allowed level, but people cannot normally get into this confined space.

4 Discussion: Future Prospect

4.1 Energy and Environment

Two basic reasons for developing OLEV buses and cars are for better air quality in large cities and the reduction of CO_2 in the earth's atmosphere to slow global warming. If we remove cars with IC engines from the streets of major cities, the quality of air will improve. However, the total reduction of greenhouse gases depends on the specific means of electricity generation, which may change more gradually. The use of OLEV may not affect the world's primary energy demand in the short term.

According to [2], the world energy use will grow at the rate of 1.6% per year on average in 2006–2030 from 11,730 MTOE[4] to 17,000 MTOE, an increase of 45%, non-OECD countries accounting for 87% of the increase. About a half of the overall increase will be because of the economic growth of China and India. The energy consumption by non-OECD countries exceeded that of the OECD in 2005. Global demand for natural gas grows more quickly, by 1.8% per year, its share in total energy demand rising to 22%. World's demand for coal increases by 2% a year on average, its share in global energy demand climbing from 26% in 2006 to 29% in 2030, which is a major generator of CO_2. The use of nuclear power will decrease from 6 to 5% relative to the increased use of energy, although the number of nuclear power plants will increase in all regions except some European OECD countries. Modern renewable technologies are growing rapidly, overtaking gas to become the second-largest source of electricity, behind coal, soon after 2010 [2].

4.2 OLEV and Supply of Electricity

To replace all IC engine cars being used in Korea in 2009 with OLEV cars, Korea needs to dedicate two nuclear power plants for electricity generation. At this time, Korea produces about 40% of its electricity using nuclear power plants. It is building eight more nuclear power plants. The cost of electricity is only 22.7% of fossil fuel in Korea.

Many countries in the world do not have any oil. These countries will have to rely on nuclear power if they are to

[4] Million Tons of Oil Equivalent.

replace all IC engine driven cars with OLEV cars and buses, without causing global warming.

To reduce the emission of CO_2, we must use more nuclear power plants and renewable energies to generate electricity. In Denmark, windmills produce about 20% of the electricity used in the country. Until we develop other green technologies for generating electric power, many countries will have to rely on nuclear power during the next 50 years. Countries like Korea are not best situated to make use of renewable energy sources. According to the International Energy Commission, the nations around the world need to build 1750 new nuclear power plants until 2050 to meet the energy needs of the world, about 35 new plants a year.

4.3 OLEV vs. Plug-In all Battery Cars

The developers of plug-in all battery cars are banking on low-cost light-weight batteries. However, there is a fundamental limit to the reduction of size and weight of any battery, because batteries need physical structures and space that do not contribute to electric power generation. Furthermore, the total known deposit of lithium is only 10 million tons. Although there is lithium in seawater, the cost of removing them will be prohibitive unless a new low-cost technology is developed.

Although these all battery cars have advantages over OLEV in the regions where the population density is so spares that the cost of laying underground coils for OLEV cannot be justified, they require many charging stations which may add significant cost. In these regions, cars with IC engines may be the best alternative.

There are many significant problems associated with implementing the all-battery plug-in car system, which include the long charging time, the high power capacity needed at charging stations, and the reduced efficiency with increase in the charging rate.

4.4 Safety

To be sure that there is no question at all about the perceived safety of OLEV, we have designed our system so that people are minimally exposed to EMF within the allowable limits. Where the exposure to the electric field is unavoidable, the magnitude of EMF is controlled to be well below the allowable level. A segmented power supply system for OLEV and specially designed coils will further reduce the EMF level to enhance safety.

4.5 Economic Competitiveness

Based on extensive analyses done, we are confident that OLEV will be much more economical than plug-in cars.

5 Summary

The On-Line Electric Vehicle (OLEV) being developed at KAIST shows promise. We have installed underground electric power coils underneath asphalt road and built an OLEV bus and an OLEV SUV to demonstrate the viability of the basic concept. We transferred electric power over a large distance from underground coils to OLEV. The system operates with sufficient transfer of power even when OLEV is not exactly on top of the underground coils.

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Process Planning and Supply Chain Integration: Implications for Design Process

L. Qiao, S.P. Lv, and C. Ge

Abstract Collaborative production among multiple enterprises is inevitable for complex product development, typically in aeronautical and astronautical engineering. There are more complex links among product design, manufacturing process and production supply chain in that area. In order to achieve their interoperation and collaboration, it is critical to transmit information between processes correctly and in good time. An initial complete product definition in design is a key to contribute to this purpose. This chapter presents the impact of process planning and supply chain design integration on the design process from three perspectives: design modelling, design methodology and design environment. A service-based collaborative framework is constructed as novel design environment for design process. A unified product information model and model-based information representation are the basis of design. And the design methodologies of design for manufacturing, design for supply chain, and design validation by simulation are adopted. The effect of the three phases as well as the integration of product design, process planning and supply chain design is discussed to sustain lifecycle information integration and consistency throughout product development processes.

Keywords Information integration · Process planning · Supply chain design · Design process · Design modeling

1 Introduction

Product design, process planning and the process of production with supply are the three imperative processes to realize a product. Integration and collaboration are the inevitable trend in modern manufacturing. Complex products such as aircraft, spacecraft etc are manufactured collaboratively by multi-enterprises, their manufacturing processes go far beyond the collaboration between the workshops within an enterprise, manufacturing resources and suppliers can be selected in larger and even the world wide range. Process planning endures greater challenges and has closer relationship with supply chain management. When firms cannot explicitly acknowledge and manage supply chain design and engineering as a concurrent activity to product and process design and engineering, they often encounter problems later in product development, such as machining problem, experiencing difficulty in assembling a component, and other problems in right time supply of materials, manufacturing process, logistic support, quality control and production costs [1]. The study of the integration of design, manufacturing and supply chain did not highly capture the enterprise managers and scholars until Fine proposed the approach to collaborative decision-making, namely, three-dimensional concurrent engineering, 3-DCE in 1998 [1]. The current research of this issue is mainly focused on three areas; empirical verification, simulation and optimization, and information integration framework and systems.

Thirumalai et al. proposed an empirical analysis of the customer expectations and satisfactions on the order fulfilment for three types of products: convenience products, shopping goods and specialty goods [2]. The investigation result showed that the supply chain design process should take into account collaboration of the product type. Based on the premise that integrating suppliers into new product development process has direct impact on the decisions in manufacturing process planning and supply chain configuration, Petersen et al. proposed a theoretical model to accomplish higher product development team effectiveness [3]. The model included the following steps: careful selection of suppliers for the new product development; involving the selected suppliers in the assessment of the technical elements associated with the project (quality, reliability, functionality, etc.); engaging selected suppliers in the business performance targets, such as costs and schedule time.

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Fine et al. offered a quantitative formulation of 3-DCE through a weighted goal programming modelling technique, and provided an tradeoff optimization method for the various objectives, such as fidelity, costs, lead time and so on, which were all considered to be of strategic relevance to the product design, the manufacturing process planning, and the supply chain design [4]. A generic simulation model was adopted by Er et al. to investigate the impact of the increasing product variety in combination with supply lead time and demand uncertainty in an international setting on supply chain performance [5]. The simulation took the upstream production plan, inner supply plan and manufacturing activities all together into account. Jiao et al. converted a problem of coordinating product, process, and supply chain into a factory loading allocation problem, and took a constraint heuristic search to facilitate the exploration of solution spaces [6].

Information integration systems are important tools to support the collaboration among product design, process planning and the supply chain design. Blackhurst et al. developed a network-based PCDM (Product Chain Decision Model, PCDM) to describe the operation of a supply chain while considering product design and process planning decisions and the impact of such decisions on the supply chain, a prototype computer system was developed based on PCDM at the same time [7]. The proposed methodology and prototype system can handle a wide variety of variables that come into play when take the product, manufacturing process, and supply chain design into consideration concurrently. Fixson proposed a multi-dimension product architecture assessment framework by applying 3-DCE [8]. The framework built on the existing product characteristic concepts such as component commonality, product platforms and product modularity. The product architecture was considered as the tie for coordinating decisions across product, manufacturing process and supply chain. An integrated order fulfilment system was designed by Zhang et al. to obtain the latest data sharing and assist companies to respond quickly to the diverse customer requirements and deliver the expected products at low costs through the configuration of product and supply programs [9].

It is obvious that the information from process planning and supply chain design is vital for a product to gain a good manufacturing and supply performance. The information of a product is the prerequisite of process planning and supply chain design, while the information of process planning towards the product is the basis to realize the product. Process planning information not only indicates the manufacturing technique content of the product [10], at the same time, it is the input of production planning and influences the preparation of production plans and supply chain design. The existence of variety manufacturing solutions for the same product provides the possibility for the supply chain optimization and dynamic adjustment via collaborative manufacturing environment. On the other hand, supply chain design can provide available or even superior supply chain information to help process engineers to design more reasonable manufacturing processes. The information of product design, process planning and supply chain design is interacted and sustained by each other. Their information integration is the basis and inevitable demand to realize the collaboration between product design, process planning and supply chain design.

To achieve effective integration of product design, process planning and supply chain design, complete and more conducive product information definition should be provided at the product design stage so as to support the lower course information integration. This chapter discusses the work on carrying out effective product information definition from three perspectives: design modelling, design methodology and collaborative design environment. A service-based collaborative framework for design process is provided, and the profound impact of process planning and supply chain design integration on product design is analyzed.

2 Process Planning and Supply Chain Design Integration

The process planning of a product is the process to design its manufacturing process and develop proper process plans including machining, assembly and heat treatment process plan according to the product characteristics such as material, geometry and tolerance etc. Supply chain design is the process to make the programming for the whole processes of goods movement starting at customer orders throughout raw materials, supply, production and distribution of finished products. On one hand, for the in-house made components, the procurement material type, quality, lead time and the production or procurement of new tooling is determined by process planning. Based on such information, and the information of the product in structures, geometric dimensions, materials and quality requirements, the enterprise can then carry out supply chain design. Decisions are made on production plan, supply plan, the extension of production plan, and supplier relationship. On the other hand, the process planning of a product is constrained by the information of supply chain quality, plan and costs. Well designed manufacturing process must be tailored to the existing manufacturing resources and supply chain resources. In order to improve the feasibility of the manufacturing process while reducing supply chain costs and ensuring that the production and supply plan can be finished according to time, quality and quantity, it is important to study the problem from the integration perspective.

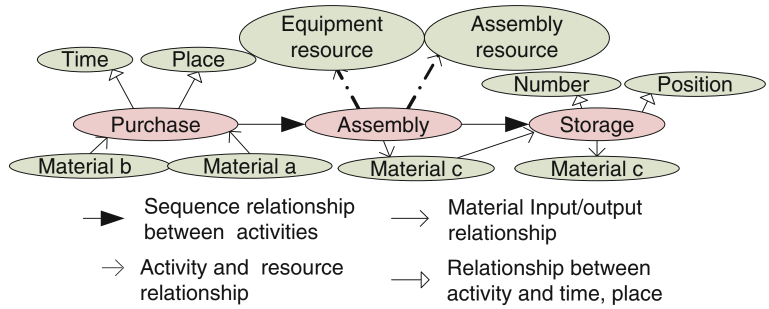

Fig. 1 AOON network example

In essence, there includes bidirectional information integration and feedback process between process planning and supply chain design. The integration of process plan information with the supply chain design process, as a fore-guidance integration process, mainly specifies the process of establishing the production plan, supply plan and the optimization and adjustment of supply chain based on the manufacturing process information. While the integration of supply chain information with process planning process is feedback-type integration. The feedback information from supply chain to process planning facilitates to design reasonable and optimized manufacturing processes.

The bottom seamless integration of manufacturing process information and the supply chain information of resource and plan is the basis of process planning and supply chain design integration. Therefore, it is necessary to induct and abstract the related business attributes, objects, relationships and processes information involved in the integration and to establish a method to express these information items.

The manufacturing process of product may have multiple process routines, operations, steps, process resources and process documents. All those objects and the relationship information between the objects are process-focused and should be organized through process [11]. For a supply chain, the related information mainly includes production plans and supply plans, scheduling results, quality, costs, inventory, production organizations, financial and material resources. As the core of supply chain, the logistics supply process is also organized in process, and it goes through a serial processes from procurement into a plant, following storage, commissioning, manufacturing, assembly, packaging, transportation, distribution and retail. In order to provide a unified organization and expression method to describe the integration information engaged in the process planning and supply chain design, a unified description method POM (Process of Manufacturing, POM) has been defined [12].

The core of POM is constituted by activity networks (AN). The time relationship, the content and semantics of process are all expressed based on the AN structure. POM is defined at present involving process network, supply chain network and implementation network. The second important part of POM is activity that specifies activities like manufacturing, purchasing, transportation, and testing, which are the events that compose manufacturing and supply chain processes. Meanwhile, an activity can also describe the cited objects involved in the process, such as product, plant, resource, organization and time. These objects describe not only the general attributes of an activity, but also contain special properties relevant to process scenario information that differs in different processes.

The formalized expression of a POM AN diagram can be built based on an AON (Activity-on-Node) network. An extension is needed from AON to AOON (Activity & Object-on-Node) network in order to express the reference relationship between activities and objects. Figure 1 shows a specific example of AOON. To facilitate the process information based on network to be identified and processed by different software platforms and systems, PSL (Process Specification Language, PSL), an international standard of process ontology was used to describe the semantics of POM, and a XML Schema modelling method has been built to provide a neutral definition of the hierarchy structure and objects in POM [12].

By means of using the POM structure, the information related to product, process planning and supply chain can well be integrated in the process network. The complex time-sequence relationship is more accurately specified in POM. Other great convenience in information transmission, sharing, and service encapsulation can be achieved by the structural and neutral description of the POM-based integrated information. Consequently information consistency throughout product design, manufacturing simulation, and supply chain design process can be obtained.

3 The Integration and the Product Design Process

The structure of a product and its components, dimensions, coordination and tolerances and materials are the characteristics that are generated during product design process

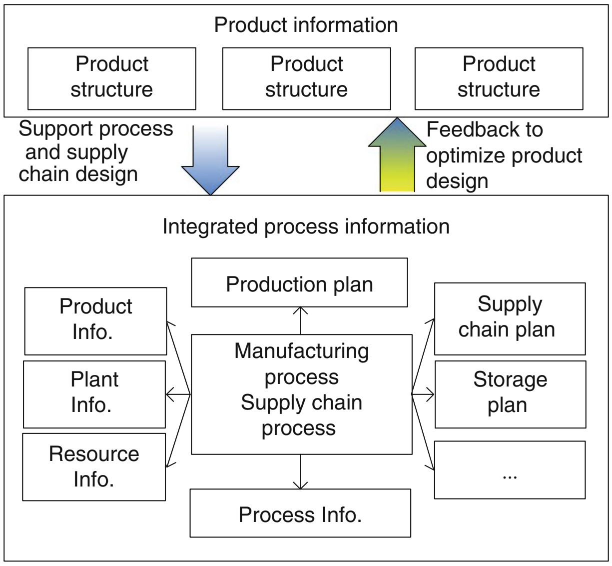

Fig. 2 Information between design and the integrated process planning and supply chain

affecting significantly the machining and assembly method, manufacturing process plans, and the selection of materials and parts. The final total costs of production and products circulation throughout supply chain depend on the product design. Therefore, it is necessary taking the manufacturing process planning and supply chain design information into consideration at the early stage of product design to perform the potential benefit to the final product as a whole.

The relationship between product design and the integrated information of process planning and supply chain design is described in Fig. 2. Product information is the input of process planning and supply chain design, while the integrated information of process planning and supply chain design is one of the important feedback decision-making references from the downstream processes for product design. In a product design, the costs, time, and quality issue for its manufacturing process should be considered. More importantly, issues such as the raw materials, new procurement tooling resource supply plans, their supply costs, quantity and flexibility should also be considered. An optimized product design can results from lifecycle support on the design scheme through the feedback assessment by process planning and supply chain, and applying the design for x (DFx) methods.

A collaborative product design environment should be created to support concurrent product design, process planning and supply chain design. In the environment, design activities are assisted by the link of process planning and supply chain design fulfilling design validations from the production process. As a result, better product design adequate to the requirement of process planning and supply chain design can be attained. There are three essential issues that should be addressed in conducting such interoperability. One is the need to build a unified product information model and its modelling approach to the expression of lifecycle information, particularly, the information for process planning and supply chain design, applying to all product development stages to ensure product and process information consistency and completion. The second issue is the use of effective design methodology including design for manufacturing (DFM), design for assembly (DFA), simulation and verification tool in the design process to achieve optimized products adaptable to the specific manufacturing process and supply chain. The third issue is to develop a collaborative design software platform to support frequent and agile information interoperation of the forward and feedback bidirectional data related to product design, process planning, supply chain design and various simulation processes.

4 Implications for Design Process

4.1 Design Modelling

4.1.1 Modelling with a Unified Product Information Model

In product design phase, not only product information but also its manufacturing requirements are generated [13], and all is the base of the subsequent manufacturing activities. It is critical task as well to construct a complete product definition that can serve lifecycle applications, in particular, the need for process planning and supply chain design. Such model should be a normalized and consistently expressed model and could maintain consistency and accuracy throughout different stages of product development to meet the requirement of collaborative design of product design, process planning and supply chain.

A unified product information model, simply refer to as eP^3R, that is the extended Product, Process, Plant, and Resource, has been developed as the foundation for information modelling and integration for product lifecycle [12]. The model is defined with three dimensions: generality, information lifecycle and service. It involves four categories of core objects: product, process, plant and resource, and several extended objects defined at present: project, plan, manufacturing instance, and the relationship between them. The information of product structure and process organized by POM makes the complex structural relationship and time-sequence relationship being modelled in a standardized, neutral and ontology semantic format. The eP^3R is able to describe the integrated information of process planning and supply chain design, as depicted in Fig. 3, and thus helps to ascertain the information to be defined in product design and

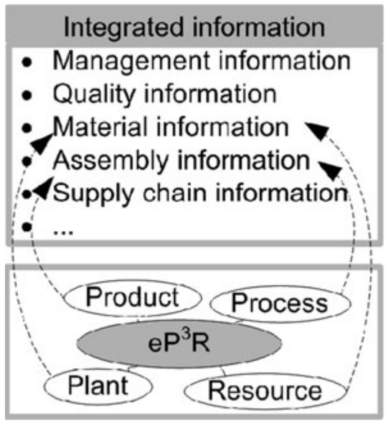

Fig. 3 eP^{3}R and the integrated information of process and supply chain

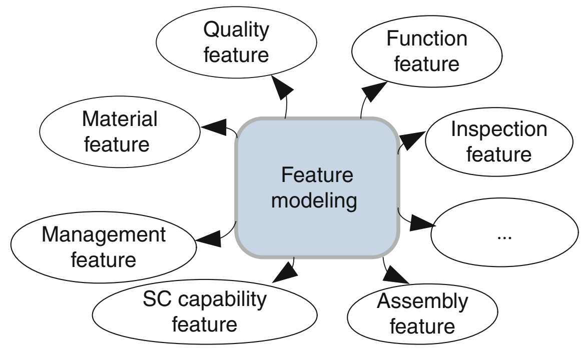

Fig. 4 Feature classification for the integrated information

process modelling. When it is used to guideline design modelling, it can benefit the accuracy and consistency of product information during lifecycle and lay the foundation for the collaboration of process planning and supply chain design.

4.1.2 Using Feature-Based Modelling

Concerning creating a design model that can better serve manufacturing process planning activities, feature-based modelling (FBM) technique should be put to use [14, 15, 16]. Gonzalez et al. proposed an information model based on the STEP AP224 standard to express the general machining features that can be recognized in CAPP system [17]. Weilguny and Gerhard defined the hole feature as user-defined features by integrating product manufacturing information during product design process to make all necessary information be transmitted to CAPP and CAM [18]. FBM can be expanded to sustain the integration of process planning and supply chain design based on the eP^{3}R at the design process.

The product feature can be classified as management feature, material feature, quality feature, function feature, inspection feature, supply chain capacity feature, and so on. All these features are linked to product, part, geometry and mating requirement in accordance with information levels and granularity. The product feature classification and feature examples of a shell-type part are shown in Figs. 4 and 5 respectively. The application of FBM during the design process steps up the goal of normalization of the product manufacturing information, and the integrity and consistency of the information required in product design, process planning and supply chain design processes.

4.1.3 The Application of Model-Based Representation

Information definition and its representation are the prerequisite for information transmission and reuse [16], as well as knowledge accumulation. With the increasing amount of product type and complexity, meanwhile, the recent development and application of the three-dimensional (3D) modelling, engineering analysis and simulation technique, the definition and representation of manufacturing information based on 3D model has become a trend and already showed its advantage. To standardize the representation of product manufacturing information in design model, several common CAD software systems such as CATIA, UG, Pro/E, have developed 3D annotation tools to realize the definition and representation of notes, dimensions, upper and lower deviation, tolerance, roughness and other information referring to the ISO 16792 standard.

There are variety of products and corresponding manufacturing requirement information with regard to different application domains. Thus there are different strategies when pursuing product definition and expression. Qiao et al. proposed an integrated process design approach based on 3D data model [19]. A FBM modelling method is applied and acted as the source of integrated information of CAD/CAM/CAPP. Chae et al. built a V2 semantic model [20]. Through the view-based product semantics in product design chain, the representation of product semantics for particular activities is realized based on the specific model view. Ding et al. adopted an approach of lightweight model with multi-layer annotation, LIMMA, to meet the requirement of the definition and representation of the information in different lifecycle phases [21].

It is suggested based on the research and practice in design and manufacturing that product and its manufacturing requirement information should be expressed together with solid model, light-weight model and feature modelling. The information affiliated to the solid model can be used for simulation and analysis, while the light-weight model is convenient to be transmitted and easy to be shared over network for concurrent collaboration. Solid model or light-weight model can be chosen according to manufacturing activities, information type and the design demand during the

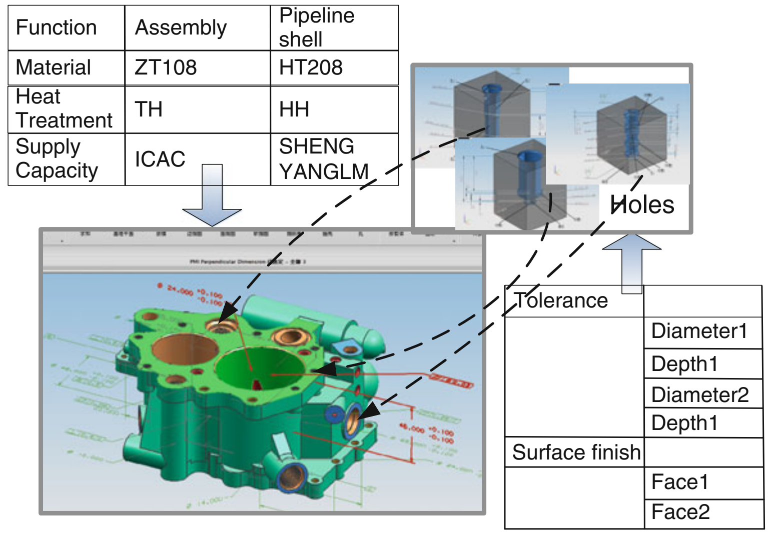

Fig. 5 Feature examples of a shell-type part

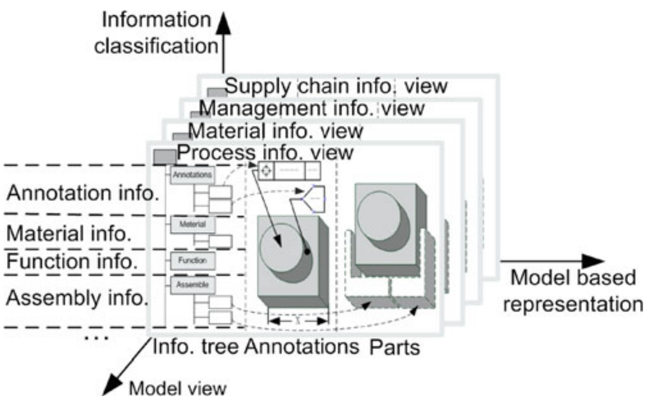

Fig. 6 Model-based information representation

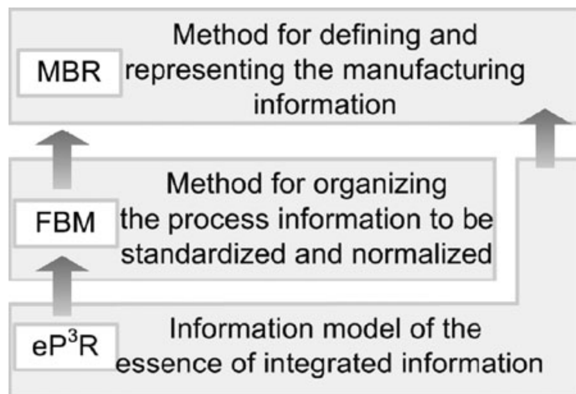

Fig. 7 General architecture of design modelling

process of definition and representation. The view of integration information can be classified through the perspective of manufacturing activities. As shown in Fig. 6, manufacturing requirement related information and product, part and its geometry can be built and organized using the format of information tree, annotations or parts. For information application and transmission, a neutral file and its data view can be created from to the model, the single data source, according to the requirement of manufacturing activity.

The eP^{3}R-based modelling method expresses the essence definition of product design and manufacturing information and their natural relationship. The feature-based modelling method can help to generate standardized and normalized product information organization, and benefit further application in lower course processes. And the model-based definition (MBR) of product information discussed above supports design and manufacturing by more direct and effective information representation with multiple process view and information type. A general design modelling architecture is illustrated in Fig. 7. It forms the modelling base of lifecycle process information integration.

4.2 *Design for Manufacturing and Supply Chain*

When more complete and more conducive design information is defined, downstream process activities receives more convenient information services. Another important work for design process improvement is to take advantage of the information effectively and then keep the product with ease of manufacturing and assembly, supply and coordination performance. The methods of DFM, DFA and design for supply chain design (DFSC) can help to meet this purpose.

Qiao et al. presented a study of design process optimization by combining top-down process and bottom-up feedback processes in product design under the guidance of concurrent engineering [22]. Collaboration between design and process planning and collaboration between trial-manufacturing and experimentation were considered in the work. Furthermore, the stochastic network planning and simulation method were used to assess the concurrent product development [23]. Howard et al. developed a knowledge-based database CAE package regarding the model as input to optimize the product through the iterative analyses [24]. Xu et al. took the advantage of fuzzy assessment method to evaluate the function, assembly, and manufacturing performance to assist design decision by importing the five quantitative assessments as good, somewhat good, etc. in the design process [25].

One of the approaches to DFx is using libraries of model templates. Different levels of template can be created in the library for an application, such as product model template, part model and manufacturing feature template. Manufacturing and supply related knowledge can be coded for the convenience of retrieval and application. Utilization of these templates during product design process facilitates the reuse of knowledge. Due to about 70% of new product design work comes from re-composition of the knowledge, while 30% other work can refer to this knowledge as well, knowledge reuse is an important way to maintain the credibility of design, accuracy of manufacturability and high productivity. Through related information support, the conflict among design, manufacturing and supply chain can be reduced, the efficiency of the design process and the manufacturing and supply performance of the product can all be enhanced. As mentioned by Aken that prescriptive knowledge models may support a more professional approach to process design [26].

4.3 Validating Design by Simulations

Simulation methods have been widely used to validate and optimize the designed program. It is an important part of product development. The performance of part machining process and assembly process can be validated by machining simulation and assembly simulation respectively during the process planning process. The simulation result is the vital feedback to product programs for product structure arrangement and material selection concerning manufacturing process evaluation and optimization. Same for the supply chain simulation. In supply chain simulation, the selection of resource, production plan and supply plan based on manufacturing process and product information can be virtually implemented, and the process information of material flows inner and outside the enterprise that composes the core of supply chain can be generated. Therefore, the supply chain simulation result is a feedback to help the improvement not only in the supply chain design itself, but also in manufacturing process planning and the product design program.

A success example of simulation support is the SAVE (Simulation Assessment Validation Environment, SAVE) project, developed by Lockheed Martin under the program sponsored by the JSF Program Office. The objective of SAVE is to develop and implement an open architecture environment to integrate design, production models and simulations to support costs, schedule and risk analysis. Rapid assessment of manufacturing impacts of the product/process decisions in product development process was made to reduce the costs [27]. Another work is from a digital factory concept proposed by Kühn [28]. In the study, the simulation of factory design in layout, manufacturing process, part machining and factory flow was integrated into a unified platform to optimize product design and process planning. With the requirement of standardization for the information interaction in the collaborative simulation platform, a Core Manufacturing Simulation Data (CSMD) has been developed in UML model and will benefit the application of manufacturing process simulation tools for design validation [29]. Commercial digital software systems like DELMIA and Plant Simulation can be available tools to assist process and resource planning, product assessment and costs analysis, factory flow simulation and manufacturing simulation.

Simulation-based approach enables to expose the potentially existed problems in design, process planning and supply chain design earlier. It also provides the reference information for process optimization and improvement. It becomes a significant tool for complex product and process design to achieve optimal product design with the most feasible manufacturing process and supply chain system.

4.4 Building a Service-Based Platform for Design Collaboration

A service is a discoverable resource that executes a repeatable task, and is described by an externalized service specification [29]. Service can provide a business process with characteristics of consistency, standardization, reusability and load-ability. The advantage of building a unified service-based collaborative design platform can be summarized as follows:

1. From data point of view, it enhances the consistency of eP^3R and product feature data being shared and transmitted with neutral document and decoupling with business. The service-based data cell can recombine the data from

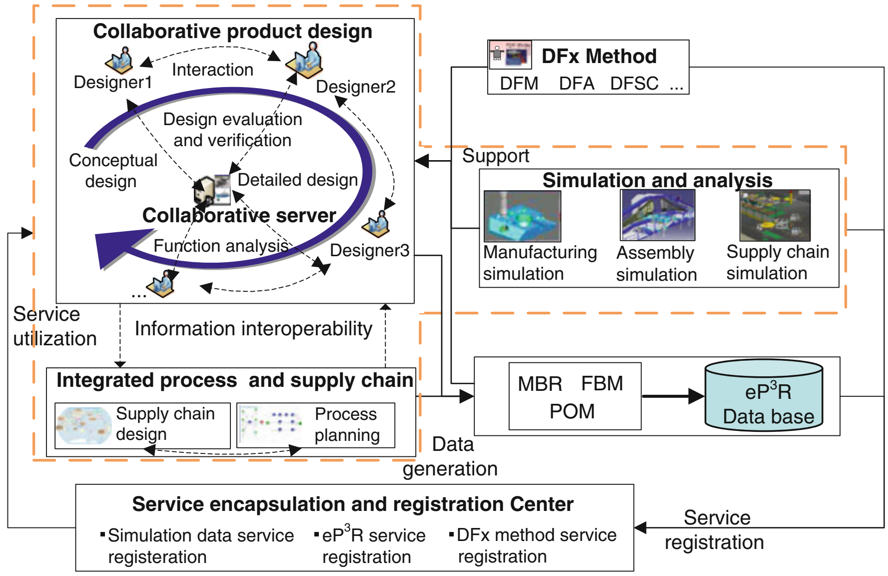

Fig. 8 A framework of service-based collaborative platform

different system, platform and stage as new service and reconstruct the business process and therefore can satisfy different business demands.

2. From collaboration point of view, service-based platform offers a normalized mechanism for the service providing and utilization, therefore, make the collaborative product design and simulation at different stages acquire the right information to finish related tasks.
3. The integration interface development can be reduced on the service-based platform. The information transmission does not depend on the concrete system but the neutral document. New extended systems can be integrated by adding service interfaces to the service-based platform.

   A framework of service-based platform is described in Fig. 8. It includes model building, service encapsulation and registration, and the application of service in the collaborative design platform and in the supportive process of DFx and simulation.

The model building that supports collaborative design and simulation is the basis of the service-oriented collaborative design platform. A unified product information model is built with the above-mentioned design modelling methodology that provides information definition and expression for the collaborative design and simulation process being organized in consolidated, normalized and standardized structure. The service encapsulation and registration consists of three parts: service encapsulation and registration of eP^{3}R, functional service encapsulation and registration of DFx method, and service encapsulation and registration of feedback assessment information from simulation platform. The essence of the application of service in the collaborative design platform and simulation process is the invocation of services. Since the service itself is platform independent, the service-based platform provides a unique information exchange environment for the integration of process planning and supply chain design. In the meantime, the collaborative product design process invokes the required services of the encapsulated feedback assessment information from simulation and DFx method to execute the DFM, DFA and DFSC and realize design collaboration practically.

5 Summary

It is a successive effort to improve product design and build an integrated product, process and supply chain co-design methodology so as to meet the demand of shortening product development cycle and reducing product costs while getting better quality for complex products development.

As downstream processes of product design, process planning and supply chain design cast profound influence on the product design. This chapter applies the process description method POM to organize and express the integrated information of process planning and supply chain design. And the impact of manufacturing process planning and supply chain design integration on product design process is expounded from three perspectives: design modelling, methodology and environment.

Design modelling applies eP^{3}R, FBM, and MBR concepts and model building methods to build a normalized and standardized unified product information model throughout product lifecycle to guarantee the information of product design, process planning and supply chain design consistent and accurate. The DFA, DFM and DFSC methods, together with the simulation tools of manufacturing and supply chain act to validate manufacturing process performance of the design in advance. Both lifecycle data and assessment feedback information are encapsulated in services in a service-based unified collaborative design platform to present an agile approach to acquiring data and affording a unified platform and mechanism for the collaboration, integration and extension of heterogeneous systems in design, manufacturing and supply chain.

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Method and Tools for the Effective Knowledge Management in Product Life Cycle

S. Tichkiewitch

Abstract The analysis of the factors linked to the life cycle of a product shows the need of the integration of the actors acting in this cycle and of their different cultures. For such integration, the concurrent engineering has to use a multi-view cooperative integrated design modeller taking into account a product model and an activity model. This modeller must be linked with a knowledge management system. This chapter presents three examples of industrial application of integrated design in the sectors of automotive, metallurgy and wood furniture's.

Keywords Integrated design · Product life cycle · Knowledge management

1 Introduction

Results of actual product designs are the combination of different concerns such as concurrency, globalization, environment, innovation, complexity or cost. The open world-wide market proposes to the customer a lot of choices that increase the concurrency among the firms, asking them to put on the market a product with short life duration at the better price. In order to reduce the costs, entrepreneurs do not hesitate to transfer the manufacturing of the product in low labour cost countries, that imply to take into account new cultures when we want to introduce the manufacturing constraints during design process, but also increase the CO_2 emission due to the logistic transportation. The reduction of the time a product can survive on the market pushes the designer to innovate to be the first on this market and to take advantage. Innovation is often the result of technology transfer and only can been done by understanding different cultures too. Complexity is link to the fact that many products are now the result of more than one technology (mechanics, electricity, electronics, software. . .) which interact the ones with the others and cannot be apprehended by only one person.

In order to take into account these global factors in the design process, we need to ask the different actors being concerned with one aspect of the life cycle of the product to act in an integrated design process. The description of this integration in design will be the subject of the second part of this chapter. In the third part, we will treat about the knowledge management as knowledge is the main object that the actors have to share. Industrial application of integrated design will be the object of the fourth and last part.

2 Integrated Design

In order to optimize the global cost of a product (cost to design, to manufacture, to put at disposal, to use and to maintain, to recycle or to destroy . . .), integration requires embracing the whole of the phases of the life cycle of the product [1, 2]. This can be made by putting in the same place the whole of the people intervening on the product at one moment or another of this life cycle. Thus we saw setting up in the 90th the "project space" at Renault or the "square field" at Facom [3]. But it is not sufficient to gather people around the same table if it is wished that they communicate. Still is necessary that they can be included by having a common culture. It is necessary to create objects of exchange to create potential links.

If each trade built a vernacular language for its own use, there exists only little of universal language allowing a common understanding. The geometry belongs to these universal languages, and this is why the CAD software developed also quickly because any trade uses the geometry. But other concepts are exchanged only by two specific trades and require to be jointly defined. These common concepts form intermediate objects, objects of mediation, basis of the vehicular

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language. It is the case for example of a bur on a stamping part which is carried out by the forger but is removed by manufacturing.

One of the effects of the globalization makes that the actors can be distant several thousands of kilometers and that they cannot be joined together around the same table. It is then necessary to create a virtual space of meeting, with access to a common database and with communications tools.

We postulate that to carry out a good integration, the actors must react to the just need. This means that an actor must be able to add to the common pot a constraint as soon as it feels the need for this constraint, but only if it can justify this need. To preserve these justifications makes it possible to spin the web of the relations binding the various data. With the just need, the product is defined by a process of emergence. The total definition of the product is done more and more finely, on the basis of a vague unit to arrive at a very precise image.

Belloy showed that a first phase of the study is the work of the technologists, people able to choose some physical principles making it possible to answer a function and to extract the various technological solutions from them [4]. They carry out coherent choices to answer the various functionalities of the problem and this until defining the set of functional surfaces. For example, these surfaces can be a technological surface (gears or bearing), a surface support of a flow of fluid (blade of a turbine) or an aesthetic surface. It is when the technologists listed the whole of the functional surfaces which it is time to join together the various actors of the life cycle of the product to make emerge a solution.

Complexity is taken within the definition of Nam Suh, based on axiomatic design [5]. In Fig. 1, the design passes from a domain to another (customer, functional, physical and process) by a linear transformation of the variables (for example of the functional requests to the parameters of design), transformation which can be put in the shape of a matrix.

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X_{11} & 0 & X_3 & 0 \\ X_{21} & X_2 & X_3 & 0 \\ X_{31} & 0 & 0 & 0 \\ X_{41} & X_2 & X_3 & X_4 \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix}$$

If the matrix is diagonal or triangular, there is a single step to pass from the functionalities to the parameters and we speak about noncomplex problem. In all the other cases, the problem is complex. The goal of a team of design is of course to find if possible a noncomplex solution to facilitate the adaptations of the parameters and to lead toward a robust design. But without knowing a priori the solution at the beginning of the design, we cannot know if the solution will be or not complex. At most can we hope for a noncomplex solution and we speak in this case about imaginary complexity.

Pimapunsri [6] proved that integrated design can solve imaginary complex problems. Each column of the matrix can be regarded as representative of a contribution of a specific trade (Fig. 2). In this matrix, one of the lines must be with only one element not equal to 0. The corresponding actors, with the just need concept, must be able to associate a value with this element making it possible to bind a parameter to a functionality and to deduce from them the influences from this parameter on the various functions to be filled. The removal of a column gives an imaginary noncomplex system of a lower order.

Like previously said, integrated design request cooperative work tools being able to be used remotely and in

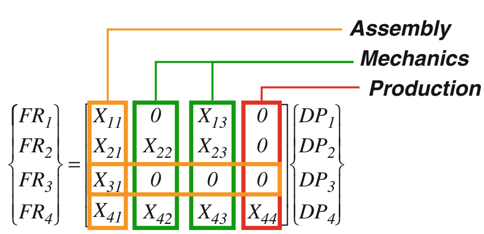

Fig. 2 The matrix of an imaginary complex problem

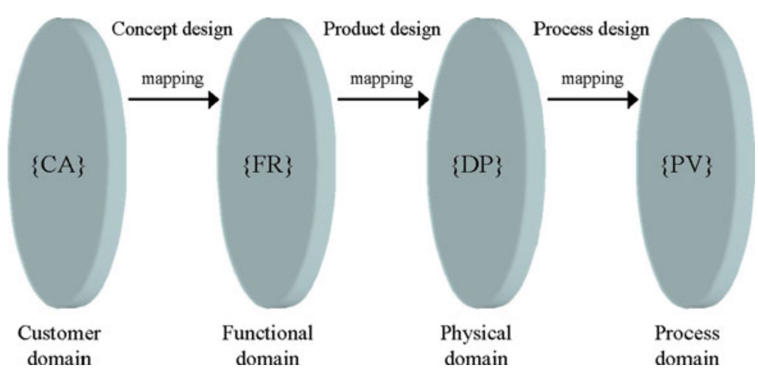

Fig. 1 The axiomatic design from Nam Suh

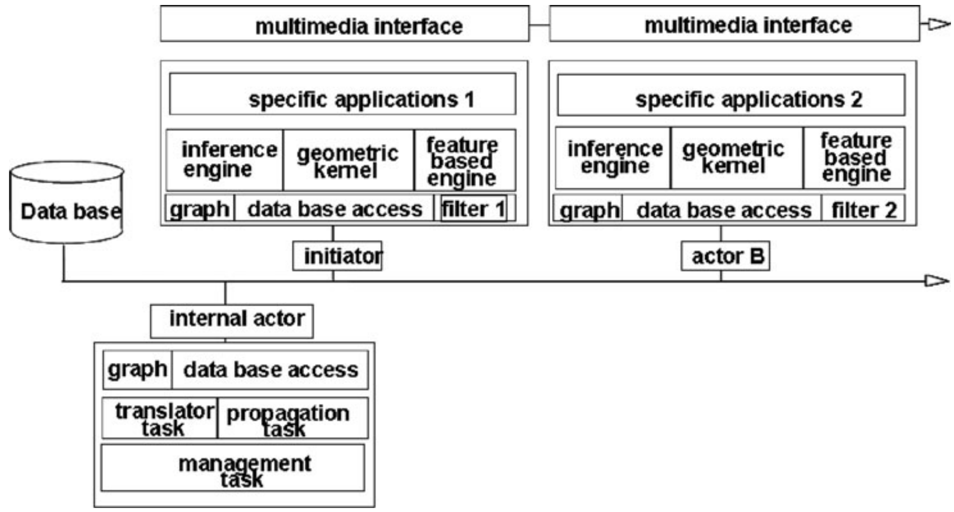

Fig. 3 The cooperative design model

a non-synchronous way. The co-operative design modeller CoDeMo was creates to meet this need [7]. Various actors can connect themselves to the same database, by representing each one a specific trade (Fig. 3). They have at their disposal some tools for the management of the access to the database, for the management of features, a geometrical engine and also tools for specific applications. A product model is used to store the whole of formal information which must be exchanged between the actors. The access to an informal communication system also allows intermediate exchanges. Some internal programs make it possible to put at disposal such tasks as translation, propagation or control of time. These tasks constitute the internal actor. We can found in [8] more information relatively the product model used in CoDeMo and the multi-view representation of the product.

3 Knowledge Management

A product model is composed of a knowledge model and a data model. Knowledge can be factual or temporal [9]. Factual knowledge is the framework of the data model. We use as factual knowledge features, with their names and their

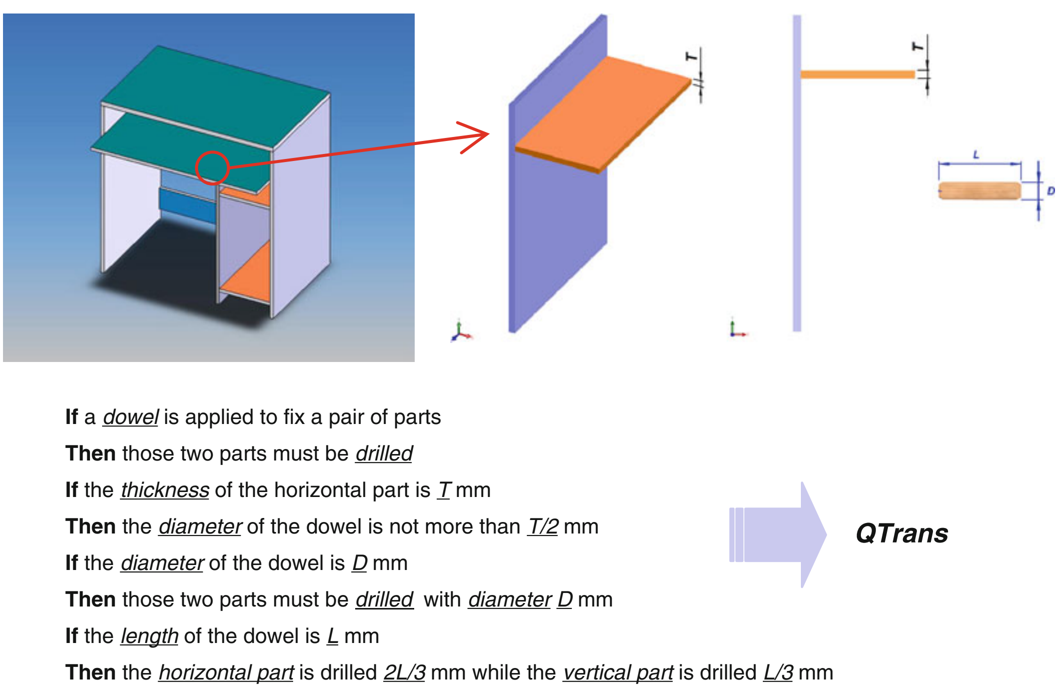

Fig. 4 Knowledge about the assembly of particle board

```
Component_Name
    Dowel Assembly name

Translation
    Component Drilling Manufacturing name_1_USI
    Component Drilling Manufacturing name_2_USI
    Link name diameter name_diameter
    Link name length length
    Link name_1_USI diameter name_1_USI_diameter
    Link name_1_USI thickness name_1_USI_thickness
    Link name_2_USI diameter name_2_USI_diameter
    Link name_2_USI thickness name_2_USI_thickness
    Relation name_diameter name
            name_1_USI_diameter name_1_USI equality
    Relation name_length name
            name_1_USI_thiskness name_1_USI 1/3thickness
    Relation name_diametre name
            name_2_USI_diametre name_2_USI equalite
    Relation name_longueur name
            name_2_USI_epaisseur name_2_USI 2L3epaisseur
@
```

Fig. 5 A translation file

contexts, their characteristics and their behaviours. Temporal knowledge is used to make progress the resolution of the problem. We use for that the production rules, with a premise and a conclusion.

Before starting any design process, the different actors have to formulate the specific knowledge of their trade using the two previous models. As an example, Fig. 4 gives a series of rules allowing the assembly of a piece of furniture in particle boards and using a solution of dowel. A dowel is defined as a feature belonging in the context of technology. Its diameter and its length are 2 of their characteristics. If we want to use a dowel to fix 2 boards, we need to drill 2 holes with some specificity. This rule permit to connect the design view (shape and size of the furniture), the technological view (the different boards and their relative positions), the assembly view (with the different possible hardware) and the manufacturing view (with tooling operations). As soon as the designer wants to use such dowel as an assembly solution, CoDeMo will use a translation file (Fig. 5) in order to inform the different actors that they are concerned. The translation file describes the evolution of the product model and CoDeMo can propagate the request in the different views.

4 Industrial Applications

We present in this part three industrial applications which help us to build the integrated design theory and the CoDeMo application.

4.1 Integration of the Recycling of a Car During Design Process

In his thesis [10], Gaucheron shows that the design of a car is very dependent of the societal and economical criteria. The ecological solutions are more expensive and can be taken into account only if the regulation imposes a minimum ratio of recyclability. It is fact impossible to introduce a recycling parameter with the traditional parameters of the design: quality, cost, weight, time. Recycling will not be taken into account in the dynamics of a project. It is necessary that there are preliminary exchanges between the designers and the recycling team to find compromise solutions well before the setting in project. This work showed the importance to define a vehicular language making it possible to have objects of shared interest between the actors. Working on the cleanup methodology for the liquid of the windshield washer, Gaucheron showed the necessity to strongly be interested in the lid of the bottle because this lid of course interests the recycling to allow the cleanup with a nozzle, but also the technology for its manufacture, the architecture for its setting in position in a situation easy to fill.

A study on the recycling of a dashboard led to a solution suggested in Fig. 6. The board is not being encumbered with multiple accessories, is easily extracted, of low apparent density and made out of polypropylene charged with linen.

4.2 Integrated Design of a Die for Aluminum Extrusion of Profiles

The design of a die for the extrusion process is not an easy task because the extrusion process is very sensitive to different parameters such as dimensions, temperature of the billet, velocity of the mandrel . . . The process cannot be simulated by numerical analysis due to the very high speed for the strain

Fig. 6 Recyclable dashboard of a Renault concept car

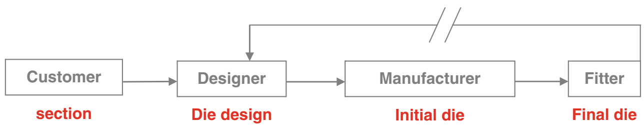

Fig. 7 The design process of a die for aluminium extrusion profile

($> 10^3\ s^{-1}$), the constitutive equation being unknown at this speed, to the non stationary, non linear and 3D problem, to the fact that flow simulation software considers rigid envelop when the tongue at the die is mainly flexible.

For economical reasons, the die designer cannot pass more than 8 h on the design of a die, which would be largely lower than the time assigned for a basic simulation. As shown in Fig. 7, the design process starts with the section for the profile requested by the customer and proposes an initial die which has to be fit during the first step of the extrusion process. Figure 8 shows that this fitting is not an easy matter to achieve and can be carried out only by fitters which have great experience. As this person is not being the initial designer of the die, it has there only very little feedback to define precise rules of design.

Noomtong added to CoDeMo [11] a case based reasoning module to capture the knowledge of the fitter and to facilitate the initial proposal for the design of a die. An example of such proposal for a hollow die is given in Fig. 9.

4.3 *Integrated Design of a Wood Furniture Made of Particle Boards or Fiberboards*

Starting from the shape and the dimension of the furniture proposed by a designer, an integrated design software for the design of wood furniture has been realised during

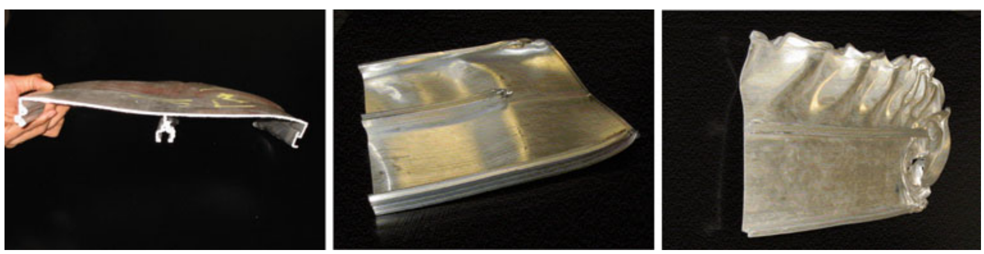

Fig. 8 Some results for the fitting of a die

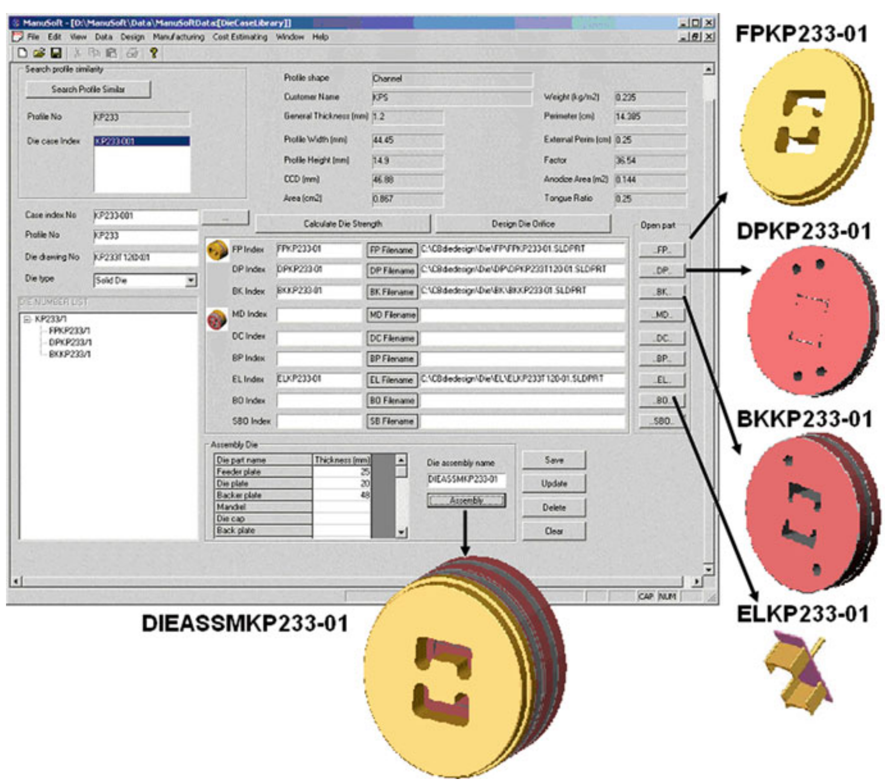

Fig. 9 The integrated die design for extrusion profile

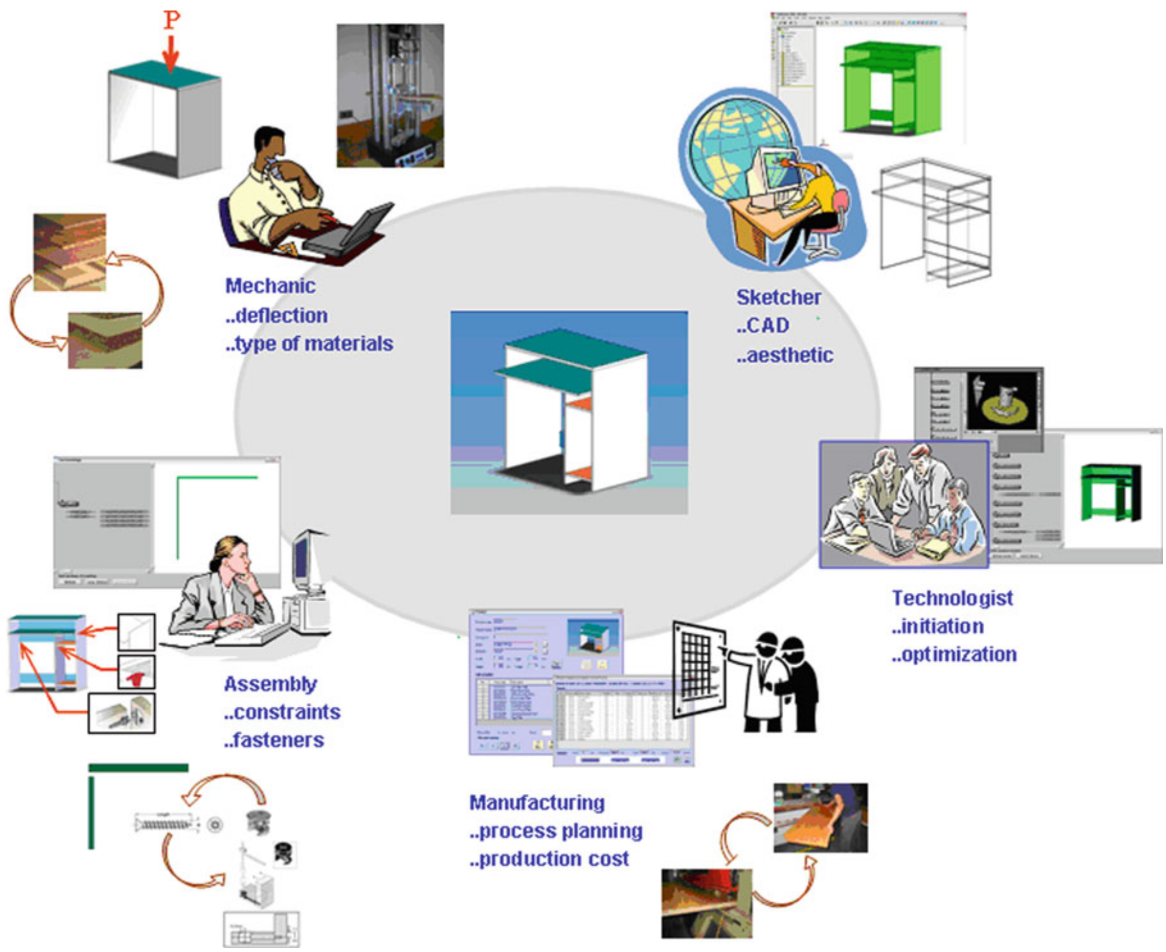

Fig. 10 Integrated design of a wood furniture

the PhD of Pimapunsri (Fig. 10). Such process needs the cooperation of the designer for the initial proposal, of the technologist for the description of the furniture in different boards, of a specialist of assembly to chose the best hardware to connect the boards, depending of the request quality and cost, the mechanical engineer to define the thickness of the board, depending of the norms and rules of the profession and of a manufacturer to define the planning and cots of the production system [12]. This work showed the capacity to design non complex solution using the integrated design process.

5 Conclusions

In this chapter, we had shown that the integration process in design is mainly a problem of coordination of actors. In order to communicate, the participants to the design process must first formalize their own knowledge before to exchange about this knowledge with the other actors in order to find some common interest and to define vehicular objects.

Using a multi-actors and multi-views cooperative design modeller, whole the actors of the product life cycle can interact on the design process with the just need concept in order to emerge the solution. This allows finding a non complex solution, key for a robust design.

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General Adaptable Product Design

P. Gu, D. Xue, and Y. Chen

Abstract Adaptable design is a new design approach for developing adaptable products to satisfy various requirements of customers. Since the adaptable design method can be used to replace multiple products with different functions with a single adaptable product, this method can reduce the costs to achieve the required functions, thereby improving the competitiveness of products. In addition, due to the decreased number of products, the waste created at the end of the product's life cycle is also reduced, thereby decreasing the impact on the environment. This paper examines the nature and characteristics of the adaptable design method by comparing it with existing design methodologies. This paper also provides details on the basic elements in adaptable design, including rationalized functions, modular adaptable architecture, adaptable interfaces, and adaptability. Research and industrial applications are provided to demonstrate the effectiveness of the developed adaptable design method.

Keywords Adaptable design · Adaptability · Design methodologies · Product life cycle

1 Introduction

Sustainable product development aims at creating products that maintain or increase value to the customer, while achieving major reductions in resource and energy usage and environmental impact. Therefore, it requires higher levels of creativity and innovation in product design and development processes.

The key aspects of sustainable product development include economical competitiveness, environmental friendliness and resource conservation in the design and development of products. To achieve economical competitiveness, products should have better functionality, higher quality, lower cost, shorter delivery time and more desirable features. For environmental and resource requirements, the criteria are often interrelated. For example, minimal environmental impact requires the minimization of resource consumption, waste generation, pollution, energy usage and so on, which are directly related to resource conservation. To maintain or increase value to the customer with these conflicting goals of product design, a new type of design is required to handle changeable product design requirements over the product life cycle.

Despite the progress achieved in the last three decades in product design theory and methodology, design requirements in current design methodologies are usually defined by a collection of unchangeable design specifications, such as target functional performance measures and manufacturing cost, and constraints in design and manufacturing. A design solution, which is usually modeled by a design configuration and its parameters, is obtained to satisfy the predefined design specifications. When customers require new or different functions in the product life cycle, new products are usually designed and manufactured to satisfy the new requirements. The used products, although still functioning or partially functioning, have to be recycled or disposed of, resulting in unnecessary resource waste and negative impacts on the environment.

To reduce the environmental impact, resource consumption and the cost to customers, the concept of the adaptable design approach was introduced to create adaptable designs and products by extending the utilities of designs and products [1].

Some design methodologies developed prior to the introduction of adaptable design can be used to partially achieve the goals of adaptable design. For example, the

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reconfigurable design method was developed to create a reconfigurable machine to achieve the functions of several machines by reconfiguration of the components of this machine [2]. The modular, product platform, product family/portfolio design methods [3] and the mass customization design methods [4] can be used to improve structures of the products, so these products can be easily changed for achieving different functions.

Compared with traditional design methods, the adaptable design approach focuses on the adaptation of products throughout their whole life cycle, rather than the reconfiguration capabilities of these products at certain product utilization/operation time points. In adaptable design, in addition to defining the design specifications that need to be satisfied at the time of product release, the requirements at different time periods of the product life cycle can also be specified. The manufactured product can be adapted at different time periods of its life cycle to meet the changed functional requirements in these time periods.

Compared with the optimal design created by traditional design methods, which achieve the best evaluation measure at a certain time point (usually the time of product release), the optimal design created by the adaptable design method can achieve the best evaluation measure considering the whole product life cycle.

2 Adaptable Design

2.1 Design Adaptability and Product Adaptability

To create a product, two processes are required, as shown in Fig. 1: the design process and the production process. The design requirements are usually modeled by engineering specifications, which are developed based on the needs of customers. The design process is the method that obtains a design solution, usually modeled by a computer-aided design (CAD) system. Production is the process that converts the design into a physical product. The design or product is evaluated based on the design requirements.

When requirements are changed due to changes in customer needs, the operating environment or technology, the manufactured product may no longer satisfy the newly changed requirements. Either the existing design needs to be adapted to create a new design and its product, or the existing product needs to be adapted directly to satisfy these changes, as shown in Fig. 1. Adaptable design, therefore, is defined as a design methodology that creates a design or product that can be easily adapted, considering changes in design requirements.

Both design adaptability and product adaptability are considered in adaptable design. Design adaptability is the capability of adapting an existing design to create a modified or new design to meet the new design requirements. By improving design adaptability, the existing design solutions and their production processes can be easily modified or reused to reduce the product development efforts and lead times for manufacturers. Product adaptability is the capability of adapting a physical product to meet the new customer requirements. By improving the product adaptability, the existing products can be easily modified, upgraded or reused to reduce the costs to the users in purchasing new products.

Design adaptability improves design efficiency by reusing design knowledge. The results developed in the past three decades in design theories and methodologies, such as cased-based design, knowledge-based design, ontology-based design, design history and rationale modeling, and design repository modeling, can be used to improve design adaptability. Product adaptability, on the other hand, is not well understood or has not been extensively studied. Since product adaptability is usually conducted by adding new components/modules, replacing or upgrading the existing components/modules with new ones, or reconfiguring the existing components/modules, the results developed in the research areas of modular design, product platform design, and product family/portfolio design are considered effective to improve product adaptability. This paper focuses on adaptable design issues of product adaptability.

2.2 Differences Between Adaptable Design and Other Design Methods

In traditional design methods, the design requirements are usually defined by a collection of design specifications. The product should satisfy these design specifications during its life cycle, as shown in Fig. 2a. Maintenance and repair of

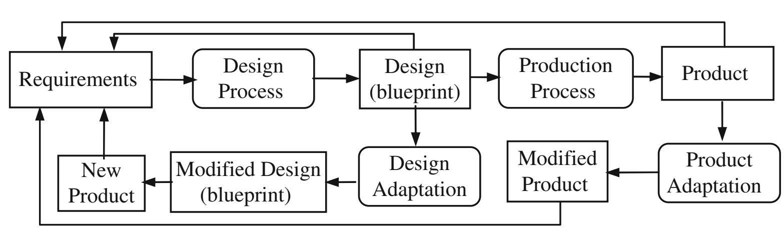


Fig. 1 Design adaptation and product adaptation in adaptable design. (modified from Gu et al. [1])

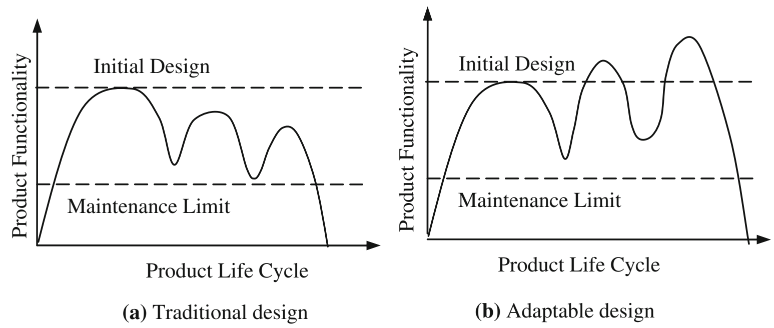


Fig. 2 Traditional design and adaptable design considering product functionality (modified from Sand and Gu [19]). (**a**) Traditional design and (**b**) Adaptable design

products are normally carried out in the product life cycle to keep and bring the functionality of the product to the level defined in the design specifications.

During the life span of the product, the original functionality of the product may need improvements that exceed the previously defined design specifications, as shown in Fig. 2b. For example, for a personal computer system with a compact disc (CD) drive and a cathode-ray tube (CRT) extended graphics array (XGA) monitor, the CD drive should be upgraded to a digital versatile disc (DVD) or Blu-ray disc drive, when higher capacity of external data access and storage is required. In the same way, the CRT XGA monitor can be upgraded to a liquid crystal display (LCD) super extended graphics array (SXGA) monitor or an LCD high-definition television (HDTV) compatible monitor to improve the resolution as well as to watch DVD or Blu-ray videos.

In adaptable design, instead of defining the design specifications using fixed design functions and constant performance measures, these design specifications can be changed at different time periods of the product life cycle. The product design should also be changed to satisfy the changeable design requirements. The design requirements, design solutions, and design functional performance measures for the personal computer system in different phases of its life cycle are illustrated in Fig. 3.

Various design theories and methodologies, such as modular design, product platform/family design, mass customization design and reconfigurable design, can be used for achieving some of the goals in designing adaptable products. Adaptable design, however, is different from these design approaches in many aspects. The differences between adaptable design and traditional design approaches are summarized in the following sections.

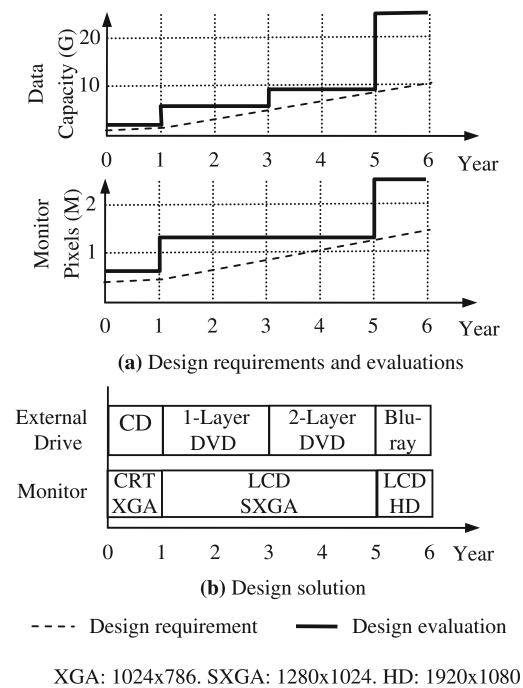


Fig. 3 Adaptable product to achieve changeable design requirements. (**a**) Design requirements and evaluations; (**b**) Design solution

2.2.1 Adaptable Design Versus Modular Design

Although modular design can be used to improve product adaptability, the products developed using the modular design approach are not necessarily adaptable and able to respond to changes in functional requirements. Modular design is often used to reduce design and manufacturing efforts by the producers.

2.2.2 Adaptable Design Versus Product Platform/Family Design

Platform design is an extension of modular design through the sharing of a common module – the platform – in all the designs of a product family. Although product platform/family design can better satisfy customer needs with a variety of products, customer needs in the form of changes in functional requirements of the purchased products are not addressed.

2.2.3 Adaptable Design Versus Mass Customization Design

Mass customization design aims at developing products based on the requirements of individual customers with near mass production efficiency. Mass customization is primarily achieved by sophisticated computer-based design systems and production planning/control systems. However, products created using this approach are usually not adaptable.

2.2.4 Adaptable Design Versus Reconfigurable Design

Reconfigurable products, such as reconfigurable machines, are considered adaptable products created to replace multiple products with a single one [2]. These multiple functional requirements, however, need to be satisfied at the time of product release. In adaptable design, however, different requirements should be satisfied in different phases of the product life cycle.

2.3 Basic Elements in Adaptable Design

Compared with traditional design methods, adaptable design is characterized by four basic elements, as shown in Fig. 4: rationalized functional structures of the product, adaptable modular architecture, adaptable interfaces and design and product adaptabilities. In adaptable design, requirements are modeled by rationalized functions. Modular architecture is employed to model design solutions that achieve the adaptable functions. Modules in an adaptable product are connected through adaptable interfaces. The design solutions are evaluated in terms of design and product adaptabilities.

2.3.1 Rationalized Functional Structures of the Product

The rationalized functions are generated through a well-defined design and decomposition process. According to [5], the design process can be represented by a mapping process from the functional requirement domain to the design parameter domain. In the adaptable design process, the design requirements are represented by functional requirements (FRs), and the design parameters are represented by design solutions (DSs). Between these two domains, we define the design process that carries out the design activities (DAs).

For each $FR_{(1)}$ at level (1) shown in Fig. 5, the DA creates a $DS_{(1)}$ at level (1). If the DS can be realized by a physical design, the design process is completed. Otherwise, for each DS, a new set of more specific and concrete functions (than the last level of functions) is defined. For this newly defined set of FRs, the DA creates corresponding DSs. The $FRs_{(i+1)}$ generated through this kind of decomposition process are necessary and sufficient. The necessity is that every FR must be satisfied by the DS, and the sufficiency of decomposition is that the fulfillment of these *n* requirements (FRs) at level (i+1) should guarantee the proper functioning of the adopted $DS_{(i)}$ for $FR_{(i)}$. The resulting hierarchical functional structure is called the rationalized functional structure. This zigzagging process completes the design process.

2.3.2 Adaptable Modular Architecture

The rationalized functions in adaptable design are achieved by a physical product that is modeled in an adaptable modular architecture. The adaptable modular architecture is characterized by a set of essential elements, including relatively independent or loosely connected modules, standard

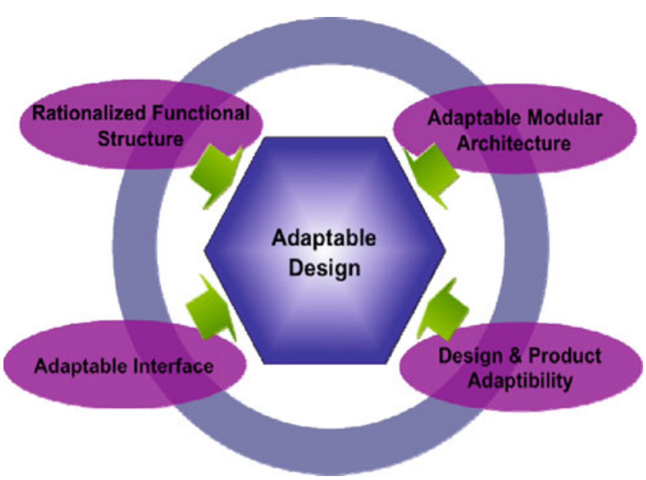


Fig. 4 Basic elements in adaptable design

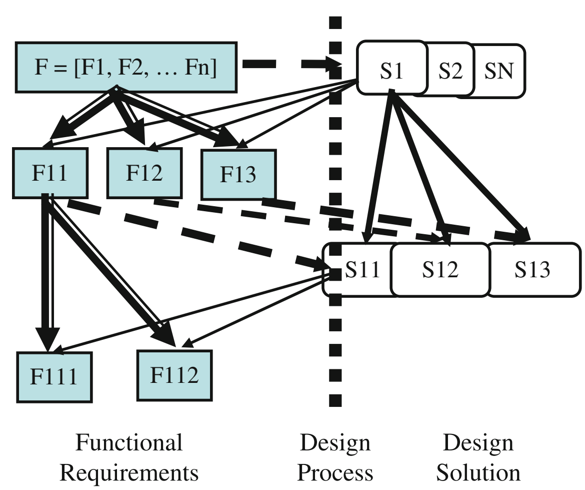


Fig. 5 Generation of the rationalized functional structure

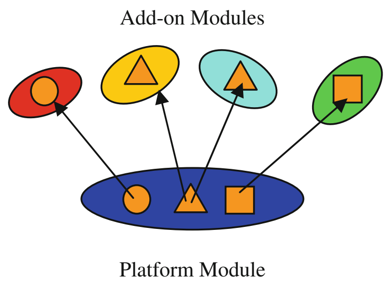


Fig. 6 Adaptable modular architecture

interfaces and layout platforms. A module is usually composed of a group of components with similar functions, technologies or physical structures.

When different functions are required, the relative independent modules of the adaptable product are then attached, detached, modified, relocated or replaced. Among these modules, some are used as bases to support and connect other modules. These modules are called platforms and are shown in Fig. 6. A product platform can also be obtained by aggregation of one or more functional modules, which is/are shared by all of products in a certain product family. Various modular design schemes can be found in [3]. Xu et al. [6] employed the parametric design approach to model the modules in adaptable design.

2.3.3 Adaptable Interfaces

Adaptable interfaces are characterized by the connections between the modules and the platforms or subassemblies. The interfaces play an important role in the realization of adaptability of products. The adaptable interfaces can be mechanical, electrical or software interfaces [7]. Electrical and software interfaces have been well reported; therefore, they are not discussed here.

An adaptable mechanical interface should be flexible, reliable and robust and is designed to achieve easy assembly and disassembly of mechanical products for rapid manufacturing, customization, repair, replacement and other life cycle objectives. Mechanical interfaces are composed of connectors with positioning and locating features, locking and release mechanisms for assembly and disassembly, and components for transmission and transformation of energy, materials and signals. A hydraulic press with mechanical interfaces is shown in Fig. 7. Various modules of this hydraulic press are connected by interfaces. Typical interfaces used in industrial applications include guiding rails and coupling devices.

2.3.4 Evaluation of Design and Product Adaptabilities

When many design solutions are created, the best one is identified through the evaluation of these design candidates.

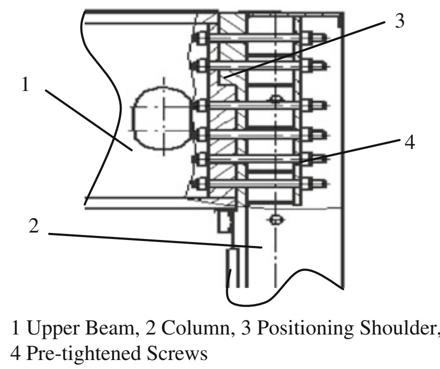


Fig. 7 A hydraulic press with modules connected by mechanical interfaces (courtesy of Tianjin Tianduan Press Co. Ltd.)

Adaptabilities are classified into design adaptabilities and product adaptabilities. Design adaptability refers to the adaptability in the design (blueprint) of a product, so that this design can be modified (adapted) to produce another product. Design adaptability aims at reusing the same design for the creation of different products. Therefore, its applicability and importance in the design process are directly dependent on the possibility of creating new products with similar designs.

Product adaptability refers to the ability of a product to be adapted to various usages or capabilities. The user (or contractor) can modify a product to achieve various functions or to enhance its performance by adding new features. The importance and applicability of product adaptability are directly dependent on the possibility of using the same product for other usages or extension of its service life as required.

3 Methodologies for Adaptable Design

3.1 Modeling of Rationalized Functions

Modeling of design functions has been extensively studied in the last three decades [8, 9]. This paper focuses on the requirements and methods of rationalized function modeling for adaptable design (AD).

3.1.1 Requirements

- When an adaptable design is used to design a product for delivering multiple functions that are usually provided by multiple products, the modeling of multiple and/or alternative functions is required.

- Due to the complexity and scale of adaptable design, modeling of functions at multiple levels is needed. In addition, these functions may be associated by their relations. These relationships should also be modeled.
- Since functions can be added, removed and modified in adaptable design, modularity and independence of functions have to be considered.

3.1.2 Methods of Rationalized Function Modeling

In the tree-based function modeling method, a complex function is decomposed into sub-functions, as shown in Fig. 8a. The overall function is satisfied by identifying the solutions to the simpler decomposed sub-functions. This scheme allows the functions to be modeled at multiple levels.

In network-based function modeling, relations among functions form a network, as shown in Fig. 8b. The relations can be modeled by different types of flows, including materials, energy and information flows [8].

In the AND-OR graph function modeling scheme introduced by Xue [10], as shown in Fig. 8c, if all its sub-functions have to be satisfied to achieve a parent function, these sub-functions are associated with an AND relation. If only one of its sub-functions needs to be satisfied to achieve a parent function, these sub-functions are associated with an OR relation. This scheme allows design requirements with multiple and/or alternative functions to be modeled.

In the axiomatic design based function modeling method developed by Suh [5], design functions are modeled by a set of functional requirements (FRs). When an FR cannot be achieved directly, this FR is then decomposed into a set of sub-FRs. In this case, all FRs are organized in a hierarchical data structure. The FRs at each level should satisfy the independence axiom to maintain the independence of the FRs.

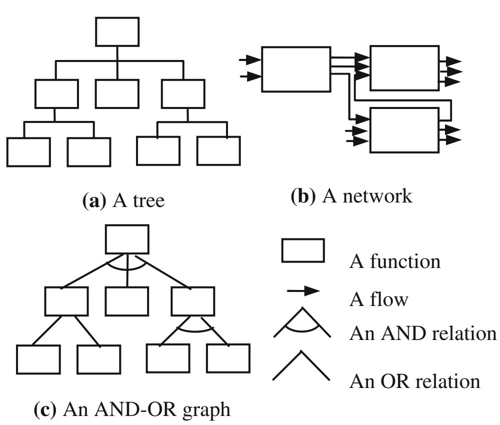


Fig. 8 Function modeling methods in AD. (**a**) A tree (**b**) A network (**c**) An AND-OR graph

3.2 Modeling of Modular Architectures

The design solutions in adaptable design are modeled using modular architectures. Research on design representation has been carried out extensively with advances of computer-aided design, knowledge-based design and life-cycle engineering design [3, 8, 11]. This paper focuses on the requirements and methods of modular architecture based design modeling in adaptable design.

3.2.1 Requirements

- Due to the complexity of product structure in adaptable design, the design descriptions should be grouped into modules and modeled at multiple levels. The relations among these elements should also be defined.
- Since a design is a solution for the required functions, the relations between design solutions and functions should be described.
- In adaptable design, multiple products can potentially be replaced by a single product. Some components/modules are used in all product configurations, while others are used in only specific models of products. Therefore, modeling of designs using a common platform and add-on accessories may be more suitable.
- Since the same functional requirements can be achieved by alternative designs, modeling of the alternative design solutions and identification of the optimal one under constraints need to be considered.

3.2.2 Methods of Modular Architecture Based Design Modeling

Tree-based design modeling is the most popular method to model the design of a product, as shown in Fig. 9a. Each node in the tree structure is used to model a component or a module. In a CAD system, such as SolidWorks, a product is modeled by a tree with leaf nodes representing parts and other nodes representing assemblies.

The AND-OR graph based design modeling method, as shown in Fig. 9b, was developed from the tree data structure to model multiple design candidates to satisfy the same design functions [10]. When a product structure can be decomposed into a number of substructures, these substructures are associated with an AND relation. When a product structure can be satisfied by alternative substructures, these substructures are associated with an OR relation. A design candidate is created from the AND-OR graph through a state-space search [10].

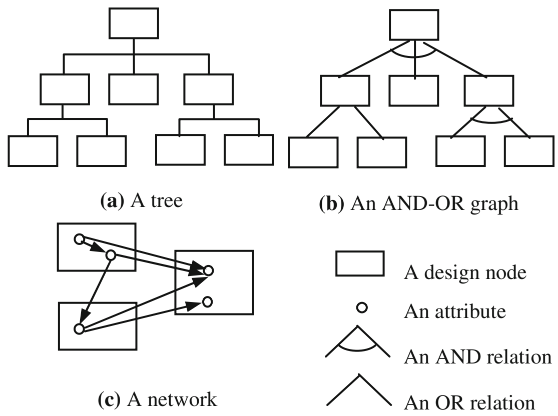


Fig. 9 Modular architecture based design modeling methods. (**a**) A tree; (**b**) An AND-OR graph; (**c**) A network

In the network-based design modeling scheme developed by Xue and Yang [12], design nodes are modeled by artifacts. Each artifact, either a component or an assembly, is described by attributes, as shown in Fig. 9c. By modeling the relations among attributes, the design nodes are associated in a network.

In the modeling of relations between design solutions and design functions in axiomatic design [5], the design functions and design solutions are modeled by functional requirements (FRs) and design parameters (DPs), which are associated by:

$$\{FR\} = [A] \ \{DP\} \tag{1}$$

When the design matrix [A] is a diagonal matrix, the design is called an uncoupled design. The design is called a decoupled design when [A] is a triangular matrix. A coupled design occurs when [A] is a full matrix. Both uncoupled and decoupled designs satisfy the independence axiom and are considered acceptable in axiomatic design.

Modular design aims at developing product architecture by using relatively independent modules [3]. A module is defined as a component or a group of components that can be disassembled non-destructively from the product as a unit. Since the modules in a modular product are relatively independent, these modules can be designed and manufactured separately. Each module can be attached, detached, modified, relocated and replaced easily for upgrading, repair, recycling or reuse. Modular design serves as a basis for adaptable design. In modular design, similar components are grouped into modules according to their functions, technologies or physical structures.

In platform and product family design, the common components for a number of products are grouped as the platform to be shared by these products [3]. The products sharing the same platform usually form a family of products. Platform design is considered as the extension of modular design through the use of a platform – the main module – in all the products of this family. In adaptable design, the functions of different products can be achieved using the platform design approach. When certain functions are required, the modules with these functions are then attached to the platform.

3.3 Modeling of Adaptable Interfaces

In adaptable design, the relative independent components and modules are connected by adaptable interfaces to achieve the required design functions. Since components and modules in an adaptable product need to be detached, attached and upgraded, the interfaces have to be considered to ensure interaction among these components and modules as well as ease of their disassembly and assembly.

3.3.1 Requirements

- Different interfaces need to be designed considering the various structures of adaptable products, such as modular structures, platform structures and product family structures.
- Since the interfaces are used to connect modules of adaptable products in order to achieve the required functions, modeling of the interfaces that consider both physical relations in design solutions and functional relations in design requirements is needed.

3.3.2 Methods of Adaptable Interface Modeling

Ulrich [13] classified interfaces in modular design into three categories: slots, buses and sectionals, as shown in Fig. 10. A slot interface is specifically designed for a certain module. The memory card port in a digital camera is a typical slot interface. A bus interface is a standard one that accepts different modules with the same type of interface. The peripheral component interconnect (PCI) bus is used for attaching peripheral devices, such as video cards and network cards, to computers. When the interfaces among modules are of the same type, these interfaces are called sectional interfaces. The studs and tubes in each LEGO brick are sectional interfaces.

Fletcher et al. [14] classified interfaces into two categories based on physical relations among the modules in design solutions and functional relations among the requirements in design functions. In additional to interfaces that are used to connect two modules or functions, interactions across the interfaces, taking into account physical relations

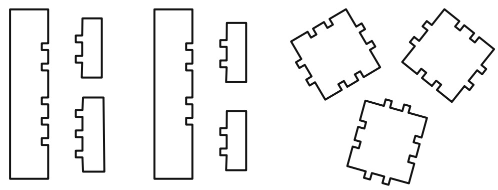


Fig. 10 Interfaces of slots, buses and sectionals. (**a**) Slots; (**b**) Buses; (**c**) Sectionals

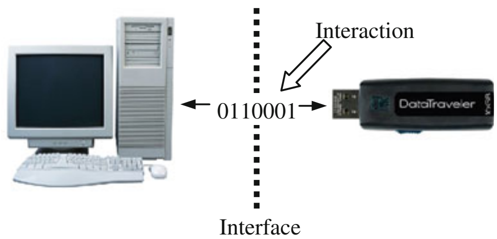


Fig. 11 Connection between a USB memory stick and a computer (modified from Fletcher [16])

and functional relations, were also introduced in this work. For example, considering the connection between a universal serial bus (USB) memory stick and a computer, shown in Fig. 11, the rectangular appendage on the USB stick that plugs into the computer is the physical interface. The electronic signal that travels across the interface is the physical interaction. The requirement to correctly align and temporarily restrain the connection is the functional interface. The requirement to add/modify/delete/copy information to or from the USB memory stick is the functional interaction.

3.4 Evaluation of Adaptable Design

The created design is evaluated, in terms of adaptability, to verify whether the goals of adaptable design have been achieved. When multiple design candidates are created from the same design requirements, these design candidates are evaluated to identify the best one for manufacturing.

3.4.1 Requirements

- Product adaptability should be classified into specific product adaptability and general product adaptability, depending on whether information for specific adaptations is available [1].
- When certain adaptabilities and their probabilities can be predicted, the product can be designed to accommodate the specific product adaptabilities.
- For accommodating some unpredictable requirements and changes, the product can be designed to have some general product adaptabilities by its product architecture and interfaces.

3.4.2 Evaluation of Specific Product Adaptability

Gu et al. [1] developed a method to measure specific product adaptability by comparing the relative efforts of product adaptation and new product creation. Suppose Tp_i is the ith adaptation task: the effort for this task, according to the information axiom in axiomatic design [5], can be modeled by its information content described by $Inf(Tp_i)$. Cost is usually used for modeling the effort. When S_1 is the current state of the existing product and AS_2 is the state after adaptation, the effort for this adaptation is then described by $Inf(S_1 \to AS_2)$. In the same way, the effort to develop a new product from scratch is described by $Inf(ZERO \to IS_2)$, where $ZERO$ is the state to design a new product from scratch, and IS_2 is the state with only the new requirements. Since less effort is usually required to adapt a product with adaptable design than to develop a new one, the relative saving of effort is modeled as adaptable factor, $AF(Tp_i)$.

$$\begin{aligned} AF(Tp_i) &= \frac{Inf_{(ZERO \to IS_2)} - Inf_{(S_1 \to AS_2)}}{Inf_{(ZERO \to IS_2)}} \\ &= 1 - \frac{Inf_{(S_1 \to AS_2)}}{Inf_{(ZERO \to IS_2)}} \\ 0 &\le AF(Tp_i) \le 1 \end{aligned} \tag{2}$$

When it takes more effort to adapt a product than to develop a new product (i.e. $Inf(S_1 \to AS_2) > Inf(ZERO \to IS_2)$), product adaptation should not be considered ($AF(Tp_i) = 0$). When no additional effort is required for product adaptation (i.e. $Inf(S_i \to AS_2) = 0$), the product is a perfect adaptable product ($AF(Tp_i) = 1$).

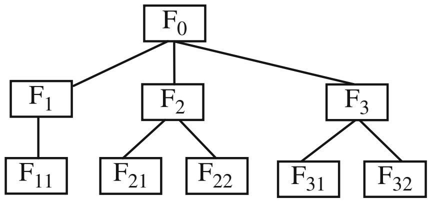
When n product adaptation tasks, $Tp_i\,(i = 1, 2, \ldots, n)$, and their probabilities, $Pr(Tp_i)$, are considered, the specific product adaptability is then modeled by:

$$A(P) = \sum_{i=1}^{n} \left[\Pr(Tp_i) AF(Tp_i)\right] \tag{3}$$

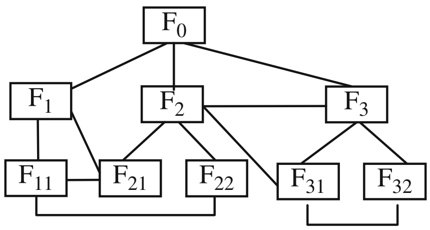
Li et al. [15] extended this specific product adaptability evaluation method by considering three types of product adaptation tasks: extendibility of functions, upgradeability of modules and customizability of components.

3.4.3 Evaluation of Generic Product Adaptability

Fletcher [16] and Fletcher et al. [14] developed a method to quantify general product adaptability. In this work, a



(a) Segregated (modular) product architecture



(b) Full product architecture

Fig. 12 Two types of product architectures (modified from Fletcher [16]). (**a**) Segregated (modular) product architecture and (**b**) Full product architecture

product was modeled by a hierarchical data structure. When only parent nodes and their sub-nodes were associated by relations, the architecture was called segregated (modular) product architecture, as shown in Fig. 12a. When other nodes were associated by relations, the architecture was called full product architecture, as shown in Fig. 12b.

The segregated (modular) product architecture is ideal for adaptable design, since modification to a node in this architecture does not impose an impact on other nodes at the same level. When an actual product is modeled by the full product architecture, its general product adaptability is measured by comparing this actual full product architecture with its ideal segregated product architecture.

The relations between two nodes are classified as interface and interaction relations. The interface describes the connection between the two functional elements, while the interaction models how the two functional modules interact across the interface. Both functional relations and physical relations are considered. Therefore, the relations between two nodes are defined by four parameters, as shown in Table 1.

A parameter is described by a value between 0 and 1, with 0 representing that a change of the *i*th node has minimum impact on the *j*th node, and 1 representing that a change of the *i*th node has maximum impact on the *j*th node. A parameter for modeling the relation between a parent node and its sub-node is assigned with 1. During the evaluation of impact between the *i*th and *j*th nodes, both the relations and importance of these nodes are considered. The importance of the *i*th node is defined by the percentage of design and manufacture efforts for creating this node in the whole product. Cost is employed to measure the effort.

Table 1 Interface and interaction parameters between the *i*th and *j*th nodes (modified from Fletcher [16])

Relation type	Physical relation	Functional relation
Interface parameter	$A_{i,j}$	$C_{i,j}$
Interaction parameter	$B_{i,j}$	$D_{i,j}$

The impact between a parent node, *i*, and its sub-node, *j*, is modeled by:

$$R_{i,j}(\min\{F_i, F_j\}) = \min\{F_i, F_j\},\quad R_{i,j} \in \{A_{i,j}, B_{i,j}, C_{i,j}, D_{i,j}\} \tag{4}$$

where $R_{i,j}$ is an impact parameter with the value of 1, and F_i and F_j are the importance measures of the two nodes. The impact between two nodes that do not have a parent-child relation is modeled by:

$$R_{i,j}(F_i + F_j),\ R_{i,j} \in \{A_{i,j}, B_{i,j}, C_{i,j}, D_{i,j}\} \tag{5}$$

where $R_{i,j}$ is an impact parameter with a value between 0 and 1.

For segregated product architecture, the total impact considering physical interface is achieved by:

$$k_A^{(S)} = \sum_{\substack{\text{Segregated}\\ \text{Architecture}\\ \text{Connections}}} A_{i,j}\left(\min\{F_i, F_j\}\right) = \sum_{\substack{\text{Segregated}\\ \text{Architecture}\\ \text{Connections}}} \left(\min\{F_i, F_j\}\right) \tag{6}$$

In full product architecture, the impact considering the extra relations is described by:

$$k_A^{(Extra)} = \sum_{\substack{\text{Extra}\\ \text{Connections}}} \left(A_{i,j}\left(F_i + F_j\right)\right) \tag{7}$$

The relative adaptability by comparing the full product architecture and its segregated architecture is achieved by:

$$k_A = \frac{k_A^{(S)}}{k_A^{(S)} + k_A^{(Extra)}} \tag{8}$$

The total relative adaptability considering the four types of relations is calculated by:

$$k = \frac{k_A + k_B + k_C + k_D}{4} \tag{9}$$

4 Applications of Adaptable Design

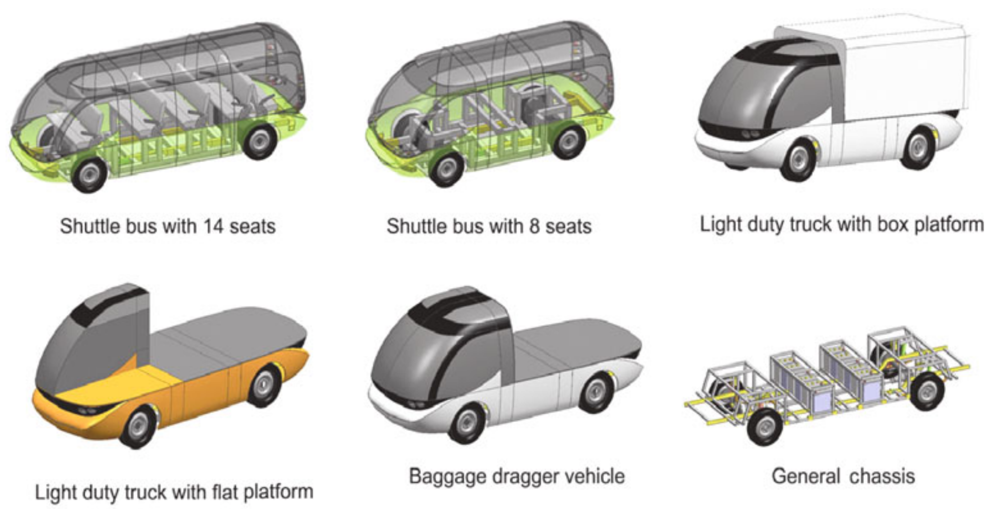
4.1 Research Application Example – Design of a Reconfigurable Transportation Vehicle

A reconfigurable transportation vehicle was developed to achieve the functions of five different vehicles, including short-distance shuttle buses with 8 seats and 14 seats, inner-city light duty trucks with box and flat platforms, and a baggage mover [17]. In this adaptable design, the FRs (functional requirements) were modeled using a hierarchical data structure; and, these FRs were mapped to DPs (design parameters), which were also organized in a hierarchical data structure. The axiomatic design approach was employed to make the FRs independent. Modular and platform designs were then used to identify the platform and add-on modules of this adaptable vehicle. Interfaces were also designed to reduce the effort of product adaptation. The final design with different configurations was modeled using a CAD system, as shown in Fig. 13a. A 1:5 scale prototype model was also built, as shown in Fig. 13b. Since the functions of the five different vehicles can be provided by this single product, this adaptable design can reduce the total costs to deliver the required five functions considerably.

The adaptabilities of this adaptable vehicle and a traditional vehicle were achieved by comparing the actual full product architectures and their ideal segregated product architectures [16]. Figure 14 shows the full and segregated product architectures of the adaptable vehicle. The cost breakdown by components is also given in this figure.

The relations of two nodes in the product architecture were modeled by four parameters that consider physical/functional interfaces/interactions. A parameter for modeling a relation between a parent node and a child node was assigned the value of 1. Other relations were assigned with values between 0 and 1, as shown in Table 2.

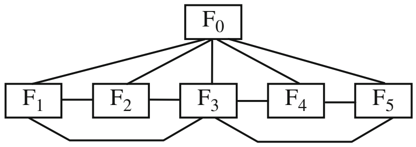
Using the general product adaptability evaluation methods developed by Fletcher [16], the four relative adaptabilities, k_A, k_B, k_C and k_D, were calculated as 0.56, 0.49, 0.64, and 0.52, respectively. The total relative adaptability was calculated as 0.55. In the same way, the full and segregated product architectures for the traditional vehicle were also developed,



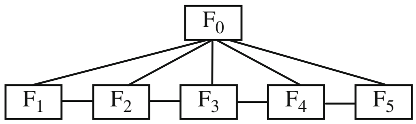
(a) CAD models with five different vehicle configurations

(b) A 1:5 scale model built using FDM (fused deposition modeling) rapid prototyping

Fig. 13 Design of a reconfigurable vehicle [17]). **(a)** CAD models with five different vehicle configurations; **(b)** A 1:5 scale model built using FDM (fused deposition modeling) rapid prototyping



(a) Full product architecture



(b) Segregated product architecture

Cost Breakdown:

F_0: Vehicle (100%), F_1: Body (20%),
F_2: Passenger compartment (15%),
F_3: Chassis (15%),
F_4: Drive-train (35%), F_5: Suspension, steering, brakes and differentials (15%)

Fig. 14 Product architectures for the adaptable vehicle (modified from Fletcher [16]). (**a**) Full product architecture and (**b**) Segregated product architecture

Table 2 Relation parameters for the adaptable vehicle (modified from Fletcher [16])

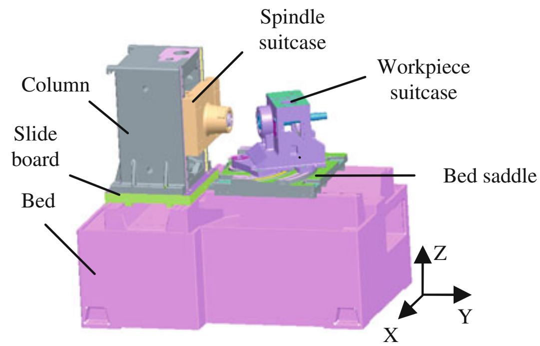
	Physical		Functional	
Relation	$A_{i,j}$	$B_{i,j}$	$C_{i,j}$	$D_{i,j}$
F_1 to F_2	0.40	0.80	0.20	0.40
F_1 to F_3	0.30	0.50	0.40	0.30
F_2 to F_3	0.30	0.30	0.30	0.30
F_3 to F_4	0.50	0.30	0.20	0.70
F_3 to F_5	0.20	0.60	0.30	0.40
F_4 to F_5	0.20	0.30	0.20	0.30

and the relations among the nodes in the product architectures were modeled. The overall relative product adaptability of the traditional vehicle was calculated as 0.43. Therefore, the adaptable vehicle is better than the traditional vehicle when considering general product adaptability based on this quantitative evaluation method.

4.2 Industrial Application Example – Redesign of Machine Tool Structure

An industrial application of adaptable design is the redesign of a machine tool structure. A spiral-bevel-gear cutting machine (YH603) was redesigned using the adaptable design method, in association with a structural analysis, to improve its dynamic performance. The structure of the machine follows the proven modular design of all computer numerical controlled (CNC) machines. Figure 15 shows the column, bed, saddle, and workpiece suitcase modules of a CNC spiral-bevel-gear cutting machine.

(a) Picture of initial product



(b) Initial design models

Fig. 15 A YH603 CNC spiral-bevel-gear cutting machine. (**a**) Picture of initial product and (**b**) Initial design models

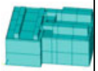
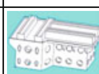
To improve the gear-machining performance and the quality of gears produced, the original structure of the machine needed improved stiffness, while its weight had to be reduced. This redesign was performed using adaptable design, and static and dynamic analyses.

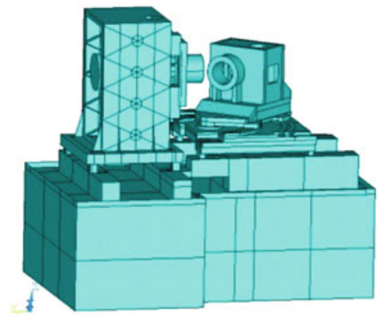
The machine structures were modeled using finite element analysis with ANSYS software. Static loading cases (cutting force on the frame) were considered. It was assumed these loading cases gave access to the properties that the designer wished to tailor and, therefore, were valid as a basis for the design. A variant of a product and/or module can be redefined and designed by changing the functional requirements or modifying the geometry of the model.

4.2.1 Criteria for the Redesign Process

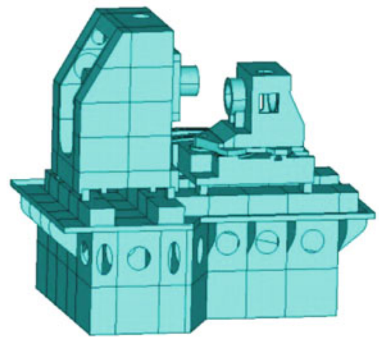
For the machine tool structural design, the first order of the natural frequency, the maximum displacement and the weight were used as the functional parameters. During the layout design of the machine, these functional parameters were calculated using finite element models to determine mass, the first three natural frequencies and the displacements to the static loading cases of the worktable, along with corresponding sensitivity information for all the design

Table 3 Structures of redesigned modules [18]

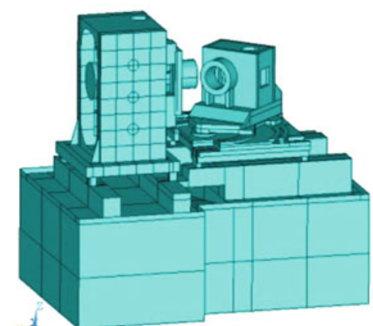
Machine Structure	Column M_1	Bed M_2	Workpiece Suitcase M_3	Slide Board M_4	Bed Saddle M_5
Original Structure S_0					
Proposed Structure S_1					
Proposed Structure S_2					
Proposed Structure S_3					
Proposed Structure S_4					
Proposed Structure S_5					
Proposed Structure S_6					



(**a**) The YH603 initial solution (P_0^1)



(**b**) The YH603 ideal solution (P_1^1)



(**c**) The YH603 actual solution (P_2^1)

Fig. 16 YH603 machine designs. (**a**) The YH603 initial solution (P_0^1), (**b**) The YH603 ideal solution (P_1^1), and (**c**) The YH603 actual solution (P_2^1)

variables. Heuristic rules were developed for structural performance evaluation including criteria, such as lightweight, high stiffness (static and dynamic stiffnesses), and manufacturing. For adaptable design, three additional criteria were proposed: performance improvement, structure similarity and adaptability [18].

4.2.2 Redesign of Machine Modules

The finite element analysis and quantitative evaluation were carried out on the machine bed, bed saddle, workpiece suitcase and column modules. The redesigned modules are shown in Table 3. In the table, S_0 represents the original design, S_i represents the ith redesigned candidate.

4.2.3 Improvement of the Entire Machine

The first step of the redesign process was to assemble the modules to obtain complete machines. The improved machines can be obtained by combining the optimal modules.

Figure 16 shows the overall machine structure and improvement solution during the design process. Based on the improved modules of the original structure of machine YH603 (P_0^1), a new structure (P_1^1) design was completed. Considering the costs of manufacturing the newly redesigned machine, a modified version of redesign (P_2^1) was adopted in order to avoid re-production of casting molds.

The following step of the redesign process was the analyses of the performance improvement and the adaptability of the functional parameters. The results of the static and dynamic analyses of the machine structures are shown in Table 4. The performance improvement of the entire machine compared to the original machine was calculated and is shown in Table 5. The adaptability of the redesign was calculated and is shown in Table 6. According to the criterion of

Table 4 Performance of the YH603 machines for the original and redesigns [18]

Design candidates	1st-order frequency (Hz)	Static rigidity of Y axis (N/μm)	Weight (kg)
Original design (P_0^1)	69.33	57.13	2890
Redesign (P_1^1)	99.03	145.82	2472
Redesign (P_2^1)	78.31	106.43	3037

Table 5 Performance improvement of the YH603 machines between the original and the redesigns [18]

Design candidates	Change of 1st-order frequency	Change of static rigidity of Y axis	Change of weight
Redesign (P_1^1)	–1.798	–1.552	–0.145
Redesign (P_2^1)	–0.130	–0.863	0.051

Table 6 Adaptability of the YH603 machines [18]

Design candidates	Structural similarity (s^{p0})	Performance improvement (E_i)	Adaptability of the redesign ($AF(S_i)$)
Redesign (P_1^1)	0.637	2.323	6.400
Redesign (P_2^1)	0.930	1.268	18.110

adaptable design of the machine tool structures, redesign P_2^1 is the best choice.

Without substantially increasing the production costs, the actual adopted redesign, P_2^1, has enhanced the functionality. Based on the existing casting models and mode analysis, ribs were added to strengthen the weak structure area. The sharp corners were changed to round corners. Other changes, such as changing the thickness of casting walls, were not adopted, as these changes would be costly. Based on the redesign of the machine tool, a new generation of machine tools has also been developed using the adaptable design method, which is given in [18].

5 Summary

Adaptable design is a new design approach for identifying products and systems that can be modified to satisfy changes in functional requirements. In this paper, concepts, methodologies and applications of adaptable design were provided. The characteristics of adaptable design are summarized as follows:

- The advantages of adaptable design are primarily economical and environmental. The user can adapt an existing product, rather than buy a new one, to achieve the new functional requirements. Compared with remanufacturing and recycling, an adaptable product can further extend its life span and reduce environmental waste.
- The four basic elements of adaptable design were discussed. In adaptable design, requirements are modeled by rationalized functions. The design solution is modeled by a modular structure to achieve the required design functions. The modules of an adaptable product are connected by interfaces. Adaptable design is evaluated in terms of design and product adaptabilities.
- Many existing design methodologies, such as modular design, product platform/family design, mass customization design and reconfigurable product design, can be employed in adaptable design. The differences between adaptable design and these existing design methodologies were also discussed in this paper.

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The Multiple Traditions of Design Research

C. McMahon

Abstract Design research has developed strongly in recent years, but it has perhaps not lived up to its early promise. In particular, industrial impact has been patchy, and impact on public policy has been poor. This paper argues that the design research community is multi-faceted. A consequence of its breadth is that it is divided, to its cost, along disciplinary and geographical lines. An overview of the design research landscape is presented, and proposals are made for the diverse traditions of the research community to come together to create an integrated view on design research, in particular for industry and the wider community.

Keywords Design research progress · Research collaboration

1 Introduction

It is necessary to start this paper with a disclaimer: these are personal reflections of the author, and while very much influenced by discussions in the Design Society (and including a number of proposals that have been made by others in the Society), they do not represent the agreed policy of the Society. However, it is hoped that the paper may foster discussion in the design community about ways in which those in the community may work more closely together in the future.

It should also be said that the paper is partly a personal reflection of the position and future of the design re-search communities but also a reaction to discussions with people from inside and outside the community that suggested that the range of different perspectives on design research was not well understood.

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Twenty years ago as a young academic I thought that we were at the beginning of a new era in design research, inspired by widespread research developments in the 1980s, and by quotes such as these from Herb Simon [1]:

> Engineering, medicine, business, architecture and painting are concerned not with the necessary but with the contingent – not with how things are but with how they might be – in short, with design

> Everyone designs who devises courses of action aimed at changing existing situations into preferred ones

> The proper study of mankind is the science of design

These were heady times to be involved in design research. The Research in Engineering Design journal quoted Simon in its opening pages. New programmes in design research were under way. New journals and conferences were starting up. I came into academia from industry where I had been a relatively early practitioner in computer-aided design (CAD), and I thought that the move towards the widespread use of CAD meant design was moving away from being centred on drafting and that by using these new tools we would be able to educate and train engineers who were more domain independent. The Moulton Report in 1976 [2], in stating

> All engineering should be taught in the context of design and design should be a thread running through the course

emphasised the importance of design in engineering education and there was a wave of enthusiasm for design education. I thought there was a real opportunity for the development of engineering curricula centred on design. We have made a lot of progress in the intervening 20 years, but much less than I had hoped. This paper presents some observations on where we have got to and where we have made less progress than might have been expected, and then presents some suggestions for a future agenda for collaboration between the research communities in design.

The paper is thus going to be in four parts. I have already presented the first – my high hopes, at the end

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of the 1980s, for design research and design education. I will next briefly review the progress in design research in the past few decades, then suggest ways in which we have made less progress than expected, in particular stressing the still fragmented nature of design research, and the (it may be argued) pre-paradigmatic status of the topic. It will then be suggested that future opportunities exist for the design research community in "cautious collaboration", and topics will be proposed for a future collaboration agenda.

2 Progress in Design

Figure 1 shows a timeline for design research since 1960. It is not intended to be definitive, but rather to illustrate the basis for my enthusiasm at the end of the 1980s. Of course the 1960s had seen the first flourishing of books of design methods – Asimow, Archer and others, as well described by Cross [3], and Simon's first edition of Sciences of the Artificial was 1969 [4]. But the 1980s had seen an absolute flourishing of books on or related to design – Hubka in 1982 [5], Schon on reflective practice in 1983 [6], the English version of Pahl and Beitz in 1984 [7]. By that time the International Conference on Engineering Design (ICED) was well established. Crispin Hales' seminal PhD thesis on the engineering design process in an industrial context was presented in 1987 [8]. The National Science Foundation (NSF) in the USA and the UK's Science and Engineering Research Council (SERC) had established programmes of research in design. New journals (Research in Engineering Design and the Journal of Engineering Design) were emerging. 1988–1991, which I have picked out in particular in Fig. 1, saw a real peak in activity with Suh and Pugh's books [9, 10], the establishment of the CIRP design seminar, the early days of the ASME DTM conference and ICED being held outside of Europe for the first time.

Those heady times have been followed by steady progress over the past 20 years. From small beginnings in Rome in 1981 the ICED conference has grown to attract about 500 participants each time it is held, and to alternate between Europe and the rest of the world. Thirteen conferences were run under the auspices of Workshop Design Konstruction (WDK), who in 2001/3 handed the baton for the conferences to the Design Society (DS). The Society has since built up a portfolio of activities including the Engineering and Product Design Education (EPDE) and NordDesign conferences, and endorsement of the Dubrovnik "Design" conferences, EDIProD, ICoRD and other events. All in all the Society has published about 3300 papers on its web site, and it is gradually working though the back catalogue of DS and WDK events.

If we look more widely, there has been a significant increase in design research publications more generally: Figure 2 shows the number of publications each year recorded by Google Scholar with the specific phrase "design research": the lower of the two curves shows the figure per million papers in total referenced by Google Scholar, showing a trebling in the rate of papers in 10 years. Of course if we look at other terms we see similar trends – e.g. for "engineering design" in 2000 there are 9360 references and 15,800 in 2008.

Of course the growth in design re-search has accompanied a revolution in design practice, in particular through the pervasive use of information technology but also as we have learned of best practices from around the world. The design office in which I worked in 1980 used entirely drawing boards and calculations were often written out by hand with the support of calculators only. I was involved in the introduction of computer-aided design into that design office

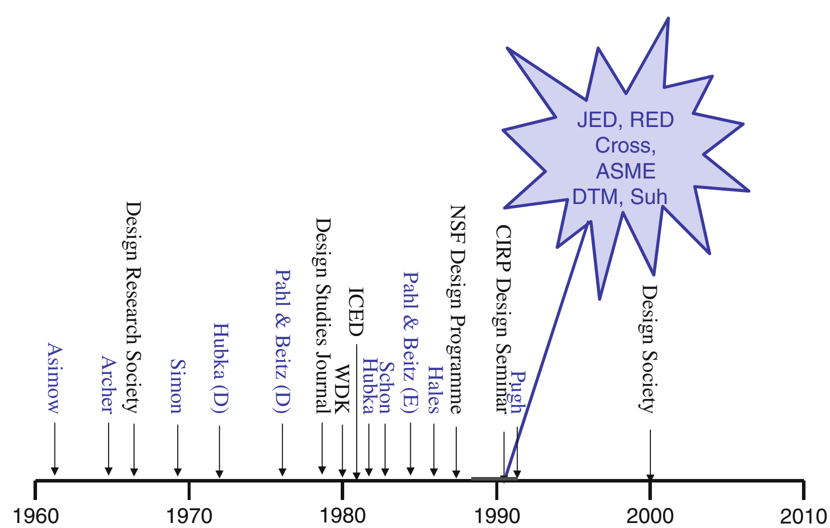

Fig. 1 A design research time-line

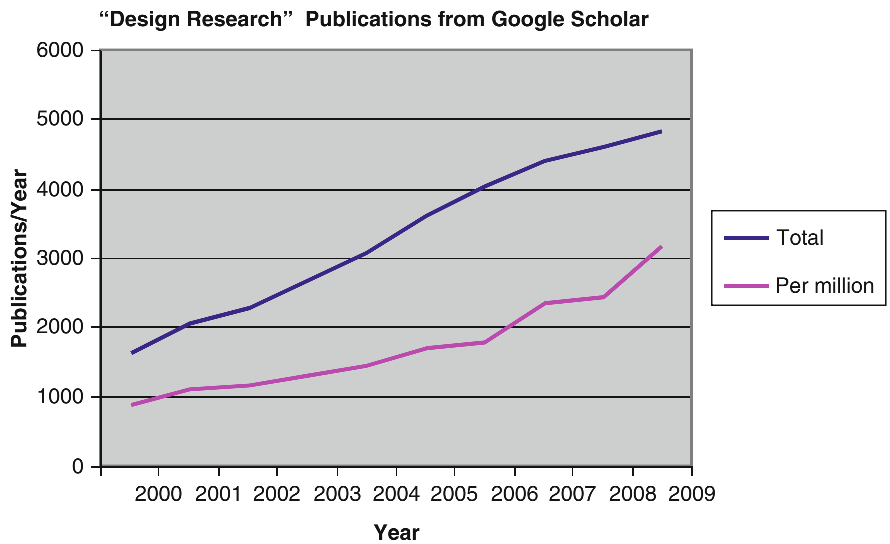

Fig. 2 The growth of design research publications

in 1981, and today an engine designer (that was the field in which I worked) would routinely use computers both for the definition and analysis of the product. There has also been a revolution in methods (but not so much the methods described in the design books of the 1960s) with techniques such as Quality Function Deployment (QFD) [11], Failure Modes and Effects Analysis (FMEA) [12] and Design for Manufacture and Assembly (DFMA) [13] in widespread use. Equally revolutionary has been the ability to physically realise 3D models through rapid prototyping. As an aside and as an illustration of what is to come perhaps, current research in my research centre through the RepRap project of my colleague Adrian Bowyer is into rapid prototyping machines that can make themselves! [14]. The open source RepRap design costs about US$400 to build. The first RepRap machine to be (largely) made by another RepRap machine made its first successful "grandchild" part on 29 May 2008 at Bath University, a few minutes after it was assembled.

We cannot discuss progress in design without also mentioning the enormous progress in design in practice. It is incontestable that everywhere we look there are superb products of design work – our cars and aircraft, buildings and civil engineering structures, high speed trains and consumer electronics to name but a few: high quality products, designed and manufactured efficiently and quickly. Clearly design practice has markedly improved over recent decades.

2.1 Has Design Research Fulfilled Its Potential?

In many ways one can be buoyed up by progress over the past 20 years, but in many ways one can be disappointed also. In design education the desire expressed by Moulton in 1976 has not really materialised. It is true that design is a mandatory part of many if not most engineering courses, but it is not really a "thread running through" the courses. Often, engineering science courses are taught much as they were (at least in the UK), with design as a separate course. We by no means teach the "sciences of the artificial" (Simon's early chapters are almost as applicable today as they were in 1969).

And while design in industry has developed very strongly, it has not been as strongly influenced by design research as one might have hoped. Many of the most popular techniques and approaches (QFD, FMEA, Taguchi methods, TRIZ, stage-gate processes) come from outside the traditional design research community and while much research is done in conjunction with industry, industry take-up and engagement is patchy, and a good deal of research still uses students as subjects of study.

But perhaps most seriously, design research is not (at least in my perception) as influential in national debates as one might expect considering the topic material that we deal with: industrial competitiveness, innovation, sustainable development, product quality and so on. With subject matter like that governments should be beating a path to our doors for advice!

We don't even influence *each other* as much as we might. The points I am going to make in the next section concern the rather silo'd nature of the design research community, but to preface these let us look at the citation rate for papers, shown in Fig. 3. Again these figures are from Google Scholar, and are for articles with a particular word or phrase, and they exclude citations for books (we have a number of highly cited books in the community – many appear on the timeline presented in Fig. 1). If we compare design research with papers from the medical or physical sciences then our citation rate is low. Of course this reflects many things – the size of the communities involved, the fact that many of

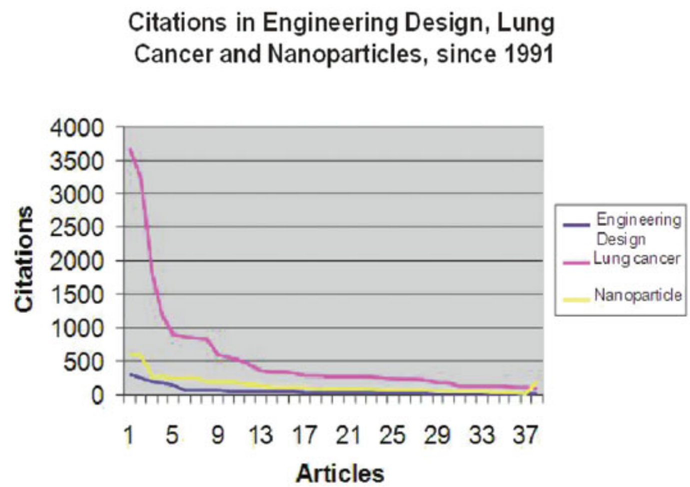

Fig. 3 Citations in different domains

our communications are not indexed by Google or Web of Science and so on (which we must correct) and the more disparate nature of our research topics, but nevertheless if we are in competition with other scientific domains then these indicators show us in a poor light. Professor Shapour Azarm makes the useful point in a guest editorial in ASME's Journal of Mechanical Design in 2009 that we should be careful not to place too much store on journal impact factors in judging journal quality, because in fields like mechanical design (unlike the medical or life sciences) research is often inspired by fundamental papers published well before the 2 years qualification period for impact factor calculation [15]. Nevertheless, we need to give research funders more reasons to think that design research is worth funding.

If we look at the communities that research in design we can see that they are many and varied: a good deal of the early work in design methods was done by the architecture and industrial/product design communities. In engineering design there are multiple communities, but mechanical and manufacturing engineers are particularly prominent in design research. Technology and innovation management is particularly pursued by management researchers, while design is of course of interest to urban planners, students of the history of technology, human-computer interaction specialists, information technologists and so on. And this does not really begin to explore those who are interested from the point of view of the design of services, as Herb Simon very much recognised.

Pahl and Beitz [7] (citing earlier work) place design at the crossing point of two spectra: from science to production and from art to politics, as shown in Fig. 4. While the completeness of coverage of that underlying diagram is arguable it is helpful in mapping the different research communities. The place of industrial/product designers, architects, furniture and interior designers and so on is clearly indicated on the diagram. Researchers into "people and systems" explore the economics/sociological part of the spectrum, and innovation management is perhaps in the top right of the crossing point. Bodies like the CIRP, ASME and Design Society are all focused near the crossing point – my feeling is that the CIRP comes from the right, and the ASME from the left, but today we all cover all of the central part of this figure, and

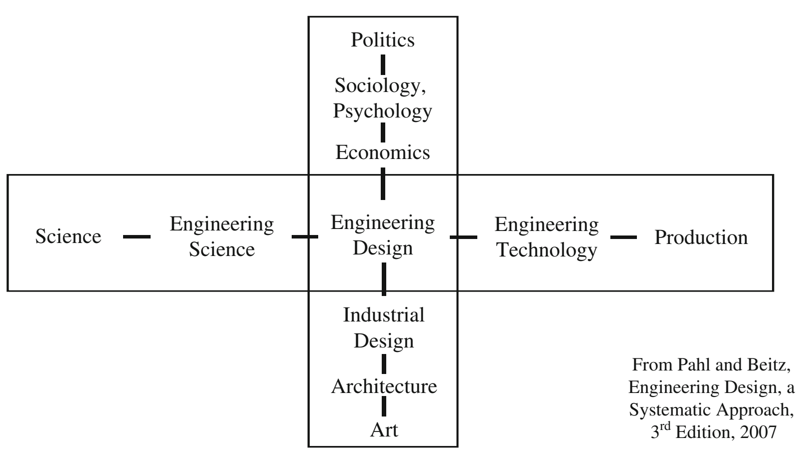

Fig. 4 Engineering design at the interface

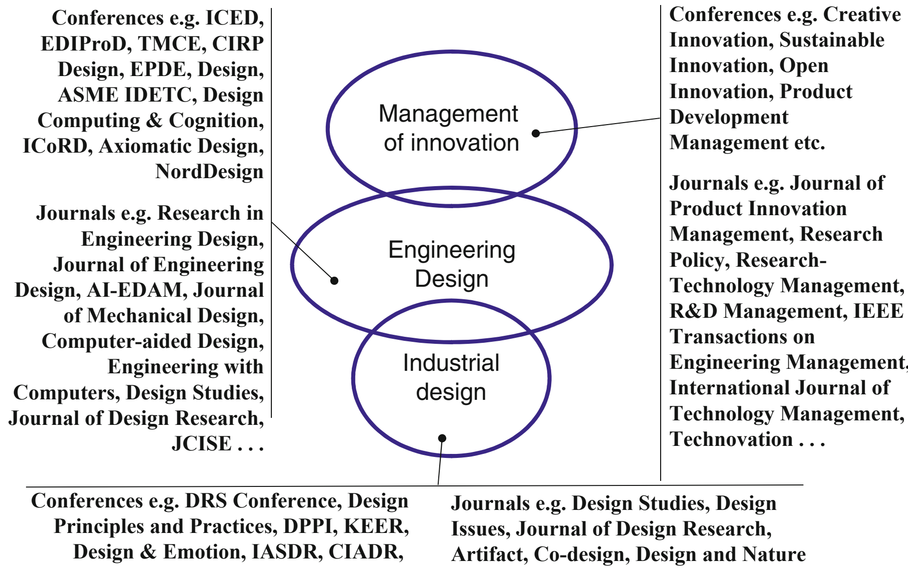

Fig. 5 Design research conferences and journals

we are all expanding our interests. Certainly in the Design Society we are very welcoming of those from the social sciences who are studying design, and we increasingly find ourselves interacting with industrial and product designers (and the focus of the Society is of course a subject for debate amongst its members).

But the divisions in the community are not just on the basis of the part of Pahl and Beitz' spectra on which we focus. We are also divided by our academic "silos" (and, as we shall see, by geographic divisions). For example, if we compare the academic affiliations of the Advisory Boards of the Design Society and of the Design Research Society we see that the former are almost entirely engineers (and dominated by mechanical engineering) while the latter are very much from the "applied arts" subjects. If we look at other communities we will see similar polarisation. And the conferences we attend and the journals we submit our papers to are different as the (very non-definitive) listing in Fig. 5 shows.

The divisions in the design community are illustrated by the lack of overlap between groups. Table 1 shows the number of authors for papers presented at the ICED'09 conference, CIRP's 2009 Design Seminar, the Design Research Society conference in 2008 and the ASME's 2008 CIE and IDETC conferences. The results for ICED, CIRP and DRS show substantially non-intersecting communities. Although there is overlap between ICED and CIRP communities it is not as strong as our relatively common technical focus would suggest it might be. And if we look at the figures for authors of ASME vs CIRP and ICED papers we see the effect of the Atlantic Ocean! And I have seen evidence when reviewing that this separation is also reflected in citations, not only in conference publications but also the journal

Table 1 Author numbers at design-related conferences

ICED09	CIRP09	DRS08	ASME IDETC/CIE08		
765	234	203	869		
ICED+ CIRP	ICED+ DRS	CIRP + DRS	ICED+ ASME	CIRP+ ASME	DRS+ ASME
47[a]	17	2	105	15	4
ICED+ CIRP+ ASME	ICED+ CIRP+ DRS	CIRP+ DRS+ ASME	ICED+ DRS+ ASME	All	
11	1	0	3	0	

[a] Authors with papers at both conferences, etc

outputs of the different communities. While these divisions are understandable for historic and geographical reasons, the problems that they lead to are of course that researchers may not be aware of important work in their fields, but also that from outside we may be regarded as a divided community.

3 Is Design Research Pre-paragdimatic?

Are the divisions we observe just the result of academic subject divisions and geography, or are they more profound than that? Shaw [16], writing about research in education, summarises the ideas expressed by Thomas Kuhn in [17] as:

> In science certain pre-eminent theories so unify an area of study that they are able to identify particular groups of problems as legitimate and urgent, as well as specifying methods for attacking them . . . these dominant exemplary models are paradigms. To have them is a sign of maturity in a scientific discipline.

How well do we meet the criteria expressed here for a mature discipline – can we identify particular groups of problems as legitimate and urgent (I believe yes, partly) and can we specify methods for attacking them (yes, but we do not agree). Pajares [18] also summarising Kuhn, suggests:

> During … early stages of inquiry, different researchers confronting the same phenomena describe and interpret them in different ways. In time, these descriptions and interpretations entirely disappear. A pre-paradigmatic school appears. … Often, these schools vie for pre-eminence.

This description seems to be more appropriate to design: we have different researchers describing and interpreting phenomena in different ways, and different schools competing for pre-eminence. If we think of some of the competing approaches in design theory and design models then this might suggest that we are pre-paradigmatic.

Or are they complementary views? Should design be viewed (again quoting Shaw [16]) as a field "concerned with fundamental concepts which are contested" (and I would add viewed as a field concerned with observations and interpretations that have insight and utility). If we are pre-paradigmatic do we need to move to be paradigmatic and if so how? If that is not the issue how do we work together to identify the important concepts, insights and their utility? My present view, influenced by Nathan Crilly at Cambridge, is that there are some parts of design research, towards the engineering science end of the spectrum (e.g. optimisation) where we are moving or we need to move towards paradigms. There are others, towards the social sciences end of the spectrum, where it is not appropriate. In this regard I believe that the interpretation of the German "Konstruktions Wissenschaft" as an "organised body of knowledge in design" (rather than "design science") is pertinent.

4 What is to Be Done?

The way forward in my view is through collaboration that nevertheless recognises and protects the interests of each party. A good phrase for this is "cautious collaboration". We see it in many current spheres – in the need to manage complex and widely geographically extended supply chains, in the global collaborations found in the automotive and aerospace industries, in the way people and industries agree to protect identities and confidentialities where important safety issues are at stake, even, more prosaically, in the recent adoption of a standard charging unit by mobile phone manufacturers.

The first act of this collaboration might be a better attempt to map the contributions of the different parts of the research community to the overall challenge of design, and the mutual recognition of our interdependency. Very crudely, in this mapping we might for example see the user's experience as the concern of the industrial design community, realising the artefact as the province of the manufacturing engineer, translating function to structure the interest of the engineering designer, research and technology management the domain of the management researcher and so on. "The designer" and "methods and tools" would be topics of common interest.

How could we move forward with such an enterprise? Could we imagine joint working parties from different parts of the community to identify and categorise topics and subtopics? Might we seek the help of the library and information science communities in this respect? And could the objective be maps of the domain for industry and public consumption as well as academic use?

To support the argument that a categorisation of our research space is necessary I include Fig. 6. This is a rather old analysis of the key words and phrases used in papers

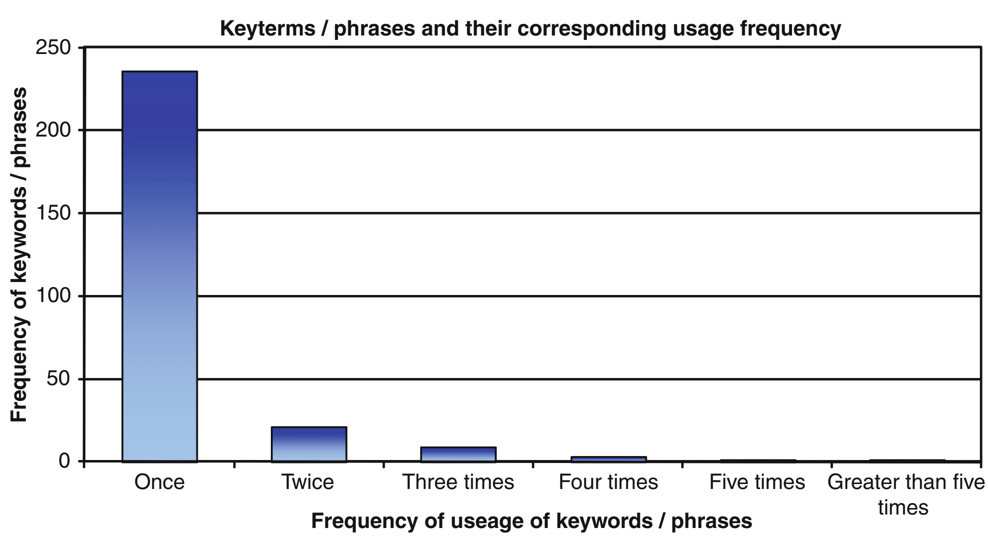

Fig. 6 Key terms and phrases used for knowledge and information papers in 1999

Table 2 DS Consolidated topic list

DS topic list used for ICED conferences
Design Processes (SIG)
Design Theory and Research Methodology (SIG)
Design Organisation and Management
Product and System Design
Design Methods and Tools
Design for X, design to X
Design Information and Knowledge
Human Behaviour in Design (SIG)
Design Education and Lifelong Learning (SIG)

submitted to ICED'99 in the broad area of knowledge and information management. You will see that the vast majority of terms are only used once. This pattern was repeated for the papers submitted to the whole conference – over 90% of terms were only used once, and nearly 1000 separate terms were used. Even with aggregation of similar terms there were over 500. We argued then, and I still argue now, that the proposal of a limited lexicon which should be used preferentially in selecting key terms would help the community in identifying relevant papers.

We might use as a starting point for a classification the consolidated topic list of the Design Society, used for the ICED conferences (the proceedings of ICED'09 match onto these topics) and shown in Table 2. This table also shows where there are Special Interest Groups (SIGs) in the Society corresponding to these topics, and the list of additional SIGs (Creativity, EcoDesign, Mechatronics, Structural Complexity, Decision Making, Computational Design Synthesis, Applied Engineering Design Science) gives further suggestions for high-level topics (but perhaps in most cases sub-topics of the consolidated list).

Another important area for collaboration, and for the design community to learn from others, is in research methodology. Questions that pertain here are:

- What would comprise the highest standards of rigour in our discipline? In that respect the contribution of Blessing and Chakrabarti's recent book on "a design research methodology" (with the emphasis on "a") is noted [19]
- What can we learn from other disciplines? As an example of what can be done the researchers in my Research Centre recently obtained funding for organisation of a lecture programme in "Social Research Methods", with speakers from a variety of research traditions [20]. The current NSF interest in interdisciplinary graduate design education in the USA is also noteworthy in this respect.
- Can we develop agreed research corpuses and examples? In many communities e.g. design optimisation or text retrieval there are standard example and corpuses that are used for test purposes by the community. This has been done in design for example in the Delft protocol studies, but can we go further?
- (This final comment is in part a reaction against the preponderance of design research using students as the subject for study). How can we better involve industry? Can we devise more extensive programmes of research studying designers in practice, for example building on the work of Badke-Schaub, Wallace and others [21, 22].

To continue the theme of educating each other and the external world, how can we make it clearer what we stand for and what we have achieved? In the Design Society we have spoken of trying to identify the key works in the community. This is of course a monumental (and contentious) task but is this something we can do together? Or could we produce joint articles or brochures for the external world?

As a final suggestion, can we envisage joint conferences or workshops on matters of shared interest? As an example, the Engineering and Product Design Education conference is already joint between, as the name implies, the engineering and industrial/product design communities [23]. The two communities share interest in educational practices, collaborative projects, the design studio, virtual design and many other topics. The International Association of Societies of Design Research (IASDR) [24] is an association of design research societies that is another potential forum for the identification of opportunities for sharing. The design research community might also consider it there are key topics that are of interest across multiple research groups that could be a focus for discussion. Priority topics that might be chosen in this respect include mapping the design research landscape, sustainable development and the challenge of creativity and innovation.

5 Conclusions

This paper has presented a personal reflection on both the achievement and lack of achievement in design research in the past 20 years. It has argued that the design research community is multi-faceted, and that a consequence is that it is divided, perhaps to its cost, along disciplinary and geographical lines. Cautious collaboration between the different parts of the research community has been presented as a possible way forward for joint work in the community, for example to map the research landscape and to identify research methodology.

Acknowledgments I would like to extend my thanks to my colleagues in the Design Society for their inputs and inspiration in the preparation of this paper.

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Evolutions of Global Product Development Approaches

Evolution Over the Life Span of Complex Systems

M. Pena, E.S. Ibragimova, and M.K. Thompson

Abstract The life span of artifacts can be viewed as a continuum. At one extreme, disposable materials, components and products go from cradle to grave with very little life in between. At the other extreme, complex systems and infrastructure can stand for decades, centuries, or millennia, slowly evolving based on performance and changing stakeholder needs. This work follows the development of the Charles River Dam in Boston, Massachusetts from its inception to the present in order to explore the design issues of complex systems over the entire life cycle.

Keywords Complexity · Ideality · Axiomatic design theory · TRIZ

1 Introduction

The life span of artifacts can be viewed as a continuum. At one extreme, disposable materials, components and products go from cradle to grave with very little life in between. At the other extreme, complex systems and infrastructure can stand for decades, centuries, or millennia, slowly evolving based on performance and changing stakeholder needs. The design issues and life cycle management of these two extremes can differ greatly. However, far less attention has been paid to the design and life cycle of large complex systems than to their mass-market and industrial counterpartsCivil systems are examples of complex systems and infrastructure which represent a different class of problems than those traditionally found in manufacturing and production systems. Civil design typically focuses on the development of unique complex systems with small (single) production volumes, very high costs, long design cycles, and very long life cycles.

Civil systems that are unsuccessful or have come to their end of life often cannot be abandoned or disposed of. They must be repaired, replaced, or redesigned. If the old system cannot be removed, then it becomes a constraint for the new system and the designers must work around it.

This work is part of an ongoing investigation to understand how formal design theories and methodologies, many of which originated in manufacturing and production, may be used to improve design in Civil and Environmental Engineering (CEE). It is also intended to investigate how CEE systems may be used to improve our understanding of design and complexity, and to improve existing formal design theories and methodologies.

This study uses Suh's Axiomatic Design (AD) Theory [1] and Altshuller's Theory of Inventive Problem Solving (TRIZ) [2] to follow the development of the Charles River Dam in Boston, Massachusetts from its inception to the present. In particular, it examines the motivations and design decisions associated with the first Charles River Dam and the environmental consequences that its construction had on the basin's aquatic life. It then explores the design decisions associated with the construction of the second Charles River Dam and the installation and eventual abandonment of an air diffuser system in the Lower Charles River Basin. At each stage, coupling, conflict, and hidden or unfulfilled functional requirements are identified and changes to the complexity and ideality of the system are discussed.

2 Prior Art

Axiomatic Design (AD) Theory has been applied to a wide variety of problems in mechanical product design [3–5], software product design [6–8], manufacturing system design [9, 10], industrial product design [11] and quality system design [12]. AD has been used in the development of integrated design for disassembly and recycling [13] and to address

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environmental considerations in product life-cycle decision making [14]. In addition, AD has been used to design a systematic framework for the structural design of a mechanical parking system [15]. But in general, examples that apply AD to civil and environmental systems are scarce.

The fusion of AD and TRIZ has a standing precedent in the literature [16, 17]. The most common approach is to employ AD to build the functional model of the system and to use TRIZ to resolve the coupling in the design [18]. Examples include the design of an eco-friendly vacuum cleaner [19], the design of paper manufacturing equipment [20], and the improvement of the acoustics in historic buildings [21]. The combination of AD and TRIZ has become so common that several studies have proposed a new synergetic theory of AD and TRIZ [22–24].

Both theories have addressed issues related to complexity or have been included in discussions of complexity. Various types of complexity and ways of reducing it were discussed by Lee [25] and Suh [26]. Several case studies which applied AD principles to analyze and reduce the complexity of systems are present in the literature [27–29]. TRIZ has also been used to address complexity in design [30, 31].

For the most part, AD and TRIZ have been used to address the design of products or manufacturing equipment with relatively short lifecycles, low cost, and low complexity compared to civil infrastructure which must operate in chaotic natural environments. We are unaware of any examples of formal design theories, including AD and TRIZ, being applied to complex system problems from civil and environmental engineering besides our own [32–34].

3 Background

This work is an extension of a previous study [32] which analyzed the evolution of Sihwa Dam in Ansan, South Korea from its construction in 1994 to the present using a combination of AD and TRIZ.

Sihwa Dam is a tidal barrage which was constructed to create a man-made freshwater lake to store agricultural water and prevent flooding of newly reclaimed land. However, the presence of the dam isolated the basin from the tides. This, combined with increased pollution in the watershed, led to major environmental problems, requiring a second version of Sihwa Dam with a tidal hydroelectric power plant to be designed and constructed. The second design, which is nearly complete, will return the tides to the basin and provide clean energy but will no longer supply fresh water to the surrounding areas.

Analysis of the Sihwa case study indicated that AD and TRIZ were able to explain some of the problems with the original conceptual design by identifying coupling and conflict in the design matrix and highlighting fundamental flaws in the decision making process that could not be reversed during later stages of design and construction. Thus, knowledge of formal design theories very early on in the design process might have been able to help avoid the costly mistakes that were made.

In this work, we continue our exploration of formal design theories with a similar case study from 100 years before: the Charles River Dam in Boston, MA. Like Lake Sihwa, the Charles River also experienced major water quality problems after the construction of a tidal dam and a second dam was constructed to address them. The methods used in both case studies were comparable. The results were both similar and surprisingly different.

4 History of the Charles River Dam

The lower Charles River which runs between Boston and Cambridge, Massachusetts was originally a tidal basin. In the 1600s, it was "a productive estuary and important source of fish and shellfish" for the local population [35]. But by the late 1800s, "thousands of gallons of untreated sewage and industrial wastewater entered the river daily through gravity drains, posing a major threat to public health" [35].

The tides exacerbated these problems. Ebb tides deposited untreated sewage on the surface of tidal mud flats which "created noxious odors and served as a breeding ground for mosquitoes that caused sporadic epidemics of malaria and yellow fever" [36].

Discussions about building a dam across the mouth of the river began as early as 1859 [37]. The dam was finally completed in 1910, forming a freshwater basin in the lower 9.5 miles of the river. The depth of the basin was increased to make the river navigable for boat traffic. Recreational parklands were created. In addition, roughly 200 acres of marshes in Allston were filled, as were salt marshes in Cambridge and Watertown [35].

4.1 Environmental Impact of the Old Charles River Dam

The original designers knew that saltwater intrusion into the basin would be a problem. A 1903 report stated that "letting in saltwater under the freshwater interferes with the vertical circulation necessary for oxygenation, and the saltwater under the freshwater soon loses its oxygen if any waster material is admitted into it." But they greatly underestimated the magnitude of the saltwater intrusion that would occur [37].

Salt water from the harbor entered the basin by seeping through the dam or by entering with the passage of ships through the lock. Once the salt water entered the basin, it was trapped. The drainage sluices in the dam were submerged by only a few feet [37]. Thus, they withdrew well oxygenated water from the upper layer, leaving the salt wedge untouched at the bottom.

Eventually, harbor water covered about 80% of the river bottom within the basin and composed about 50% of its depth [38]. During the summer of 1957, salt water covered almost the whole length of the basin and chloride levels at North Beacon Street bridge, approximately 7 miles above the Charles River dam, were as high as 10,200 mg/l at an 8-ft depth [36]. Dissolved oxygen levels at the bottom of the salt wedge were consistently near 0 mg/L leaving the water unable to support aerobic life.

4.2 The New Charles River Dam

"In 1978, the US. Army Corps of Engineers built a second dam about 2,500 ft downstream of the original dam" [35]. The new dam had "two small boat locks for the majority of recreational boat traffic and one large lock for peak recreational and commercial traffic" [38]. The new design of the locks and sluices was expected to "result in an 80% reduction in salt water instruction" [39] in part because the locks were "designed to always empty water into the harbor" through a culvert and wetwell pumping system [40].

Six flood control pumps were incorporated into the new design which could "maintain a constant basin water level when the level of Boston Harbor exceeds that of the basin, and upstream flood waters would otherwise inundate" the surrounding areas. "Such flooding occurred during two large hurricanes in the 1950s" [35].

Salt water drainage was a key concern of the designers of the second dam. The flood control pumps were just one way in which the new dam could remove salt water from the basin. In addition, "a deep culvert filling and draining system" in the locks could be used to remove salt water, as could the upper and lower sluice gates, and the fish ladder [35]. The upper sluice gate is 10.5 feet below the normal basin water level. The lower sluice gate is 21 feet below the normal basin water level and is used to drain the salt wedge at low tide [40].

In 1979 an artificial destratification system was installed in the lower Charles River Basin to induce mixing and maintain dissolved oxygen levels above 4 mg/l throughout the basin [39]. This was achieved by pumping compressed air to the bottom of the river and then releasing it through a series of six diffusers located in the deepest sections of the Charles. The upwards motion of the bubbles entrained water, creating vertical mixing currents [39]. The mixing also brought the bottom salt water layer to the surface, allowing it to flow out to sea.

These changes were also accompanied by on-going efforts to reduce the pollution in the basin and re-route waste water to treatment plants.

4.3 Recent History

The artificial destratification system was successful in increasing dissolved oxygen and reducing salinity levels in the basin [39]. Unfortunately, its success was not long-lived.

"The MDC operated the air-mixing diffusers for approximately 8 years. Diffusers 1, 2, and 3 ceased operating in 1986 due to operational procedures and diffusers 4, 5, and 5A stopped operating as a result of compressor failure around 1986. As a result of budget cuts, no repairs were made and maintenance and operations staff [were] cut. However, one airless compressor was installed at the Fens Gatehouse in 1991 but due to lack of operational staff, it has not been operated on a regular basis" [41].

By 1988, researchers noticed that the "bottom waters of the river were returning to their pre-1979 state." And by 1990, "there was no longer any doubt that the saltwater and [dissolved] oxygen stratification was back" [41].

The second Charles River suffered from similar problems. The improved lock system has not performed as well as was hoped. "The wet well is seldom used to pump lockwater into the harbor [at high tide], partly because the wetwell valves and pumps are in poor condition and costly to maintain" [40].

The fish ladder, too, has had problems. In 1991, the US Army Corp of Engineers reported that "effective upstream fish passage through the fish ladder is severely limited because the floating weir is damaged and the diffuser pipes are partially blocked." They predicted that most fish probably accessed "the basin through the locks during normal boat locking operations." Unfortunately, boat lockings are "infrequent during early spring, upstream smelt migrations." Fortunately, downstream migrations seem to be less severely affected [40].

5 Methods

In this work, four states of the Charles River Dam are considered: the tidal basin before 1910 and the construction of the first dam, the original Charles River Dam, the new Charles River Dam as it was originally intended, and the current state of the basin without a functioning bubbler system. For each state, functional requirements (FRs) and design parameters (DPs) are defined and formal design matrices based on Suh's Axiomatic Design Theory were constructed.

The FRs, DPs, and design matrix for each state are based on information from the literature (summarized above) and attempt to reconstruct the thoughts and actions of the designers. As a result, they provide a useful representation of the evolution of the system being considered, but may not be an accurate representation of the actual design process.

Each design matrix was analyzed to identify coupling based on AD's first axiom (the Independence Axiom) and conflict from TRIZ to determine if these were responsible for some of the problems that developed as a result of the various designs. AD's second axiom (the Information Axiom) and TRIZ's Law of Ideality were also used to examine the difficulties that the designers faced and to evaluate the decisions that they made. Although there is a distinction between physical and technical contradictions in TRIZ, we did not make the distinction in this work.

We were primarily interested in identifying problems which were introduced at the very early stages of the design process, rather than focusing on the details of each design iteration. As a result, the FRs and DPs for each design matrix reach a maximum of 5 levels of decomposition.

6 Design Matrices for the Charles River Dam

6.1 Design Matrix for the Natural System

In tidal systems, the movement of the water helps to maintain water quality and to ensure a productive and stable ecosystem. Thus, the tides can be thought of as performing a variety of functions to protect the environment.

The functions performed by the lateral movements of the water include transporting nutrients into the basin and contaminants out of the basin. The vertical motion of the water regulates dissolved oxygen and salinity levels.

For this type of system, the only design parameters are the tides, and tidally induced currents. Thus, natural tidal estuaries are fully coupled periodic systems (Fig. 1). This, in turn, implies that they are also very complex systems and that the consequences of human intervention may be difficult to predict.

6.2 Design Matrix for the Old Charles River Dam

The original Charles River Dam was intended to provide a number of benefits to the surrounding communities.

Charles River Dam that would address environmental issues.

To reflect this situation, we have included the additional functional requirements (FRs) associated with water quality in the design matrix but many of the related design parameters (DPs) are missing. The entries in the design matrix column associated with the missing DPs have been removed since no relationship with those DPs is possible.

6.3 Design Matrix for the New Charles River Dam

The designers of the second Charles River Dam intentionally set out to address the environmental problems that developed as a result of the first dam. The new dam included functions to control the water level at high and low tide, and under normal and emergency conditions to prevent flooding. It also included a number of new functions to minimize the salt water intrusion into the basin, to remove the salt which did

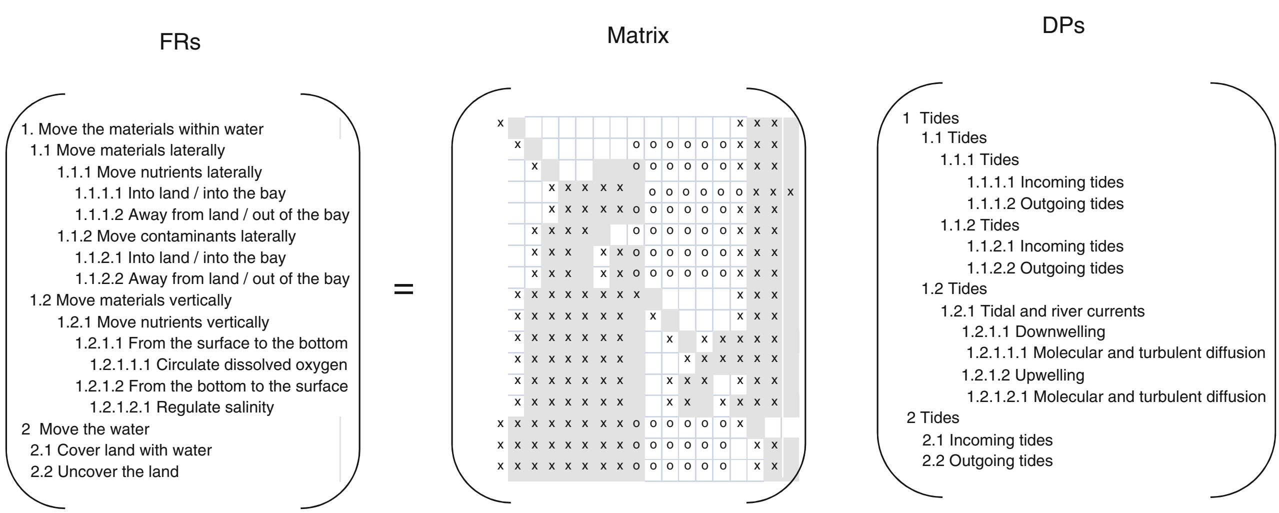

Fig. 1 Design matrix for the natural system

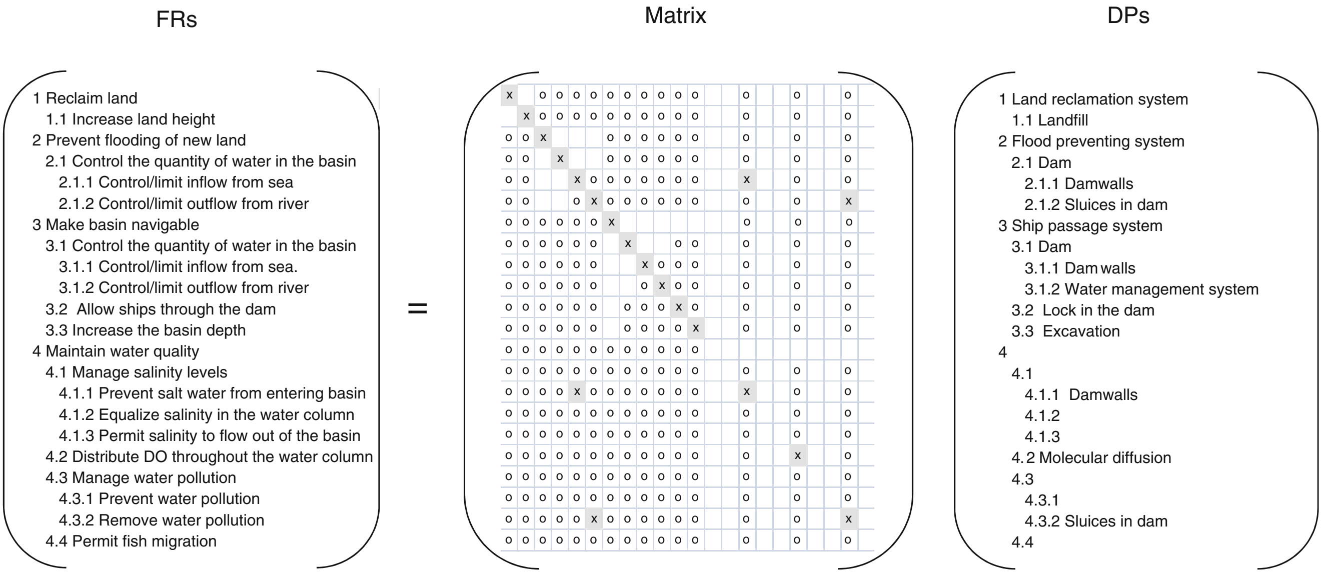

Fig. 2 Design matrix for the new Charles River Dam

enter the basin, and to minimize the environmental impact of the salt wedge (Fig. 2).

One of the most noteworthy features of the second dam was the artificial destratification system. By installing a mechanical system to induce vertical mixing currents in the basin, the second design was attempting to replace some of the functions that were lost with the construction of the first dam.

6.4 Design Matrix for the Present

The design matrix which represents the current state of the Lower Charles River Basin is shown in Fig. 3. The functional requirements are mostly unchanged from the previous matrix. However, some of the design parameters have been changed or removed.

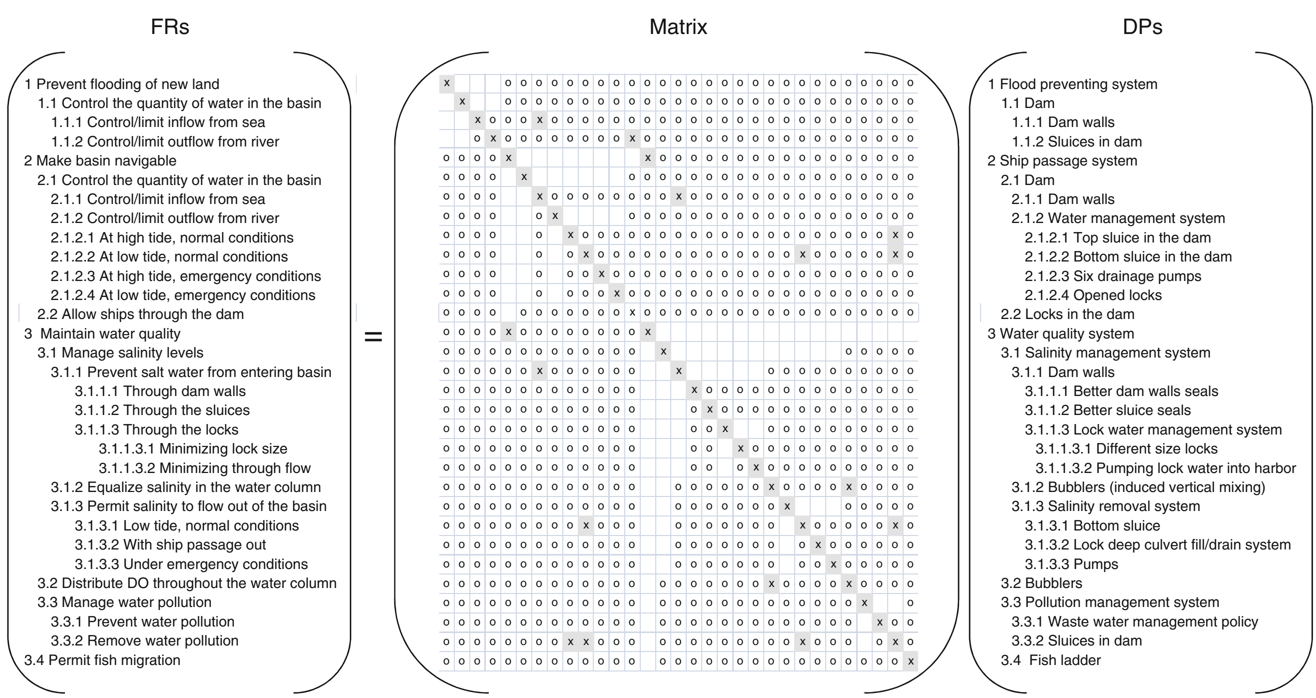

Fig. 3 Design matrix for the present

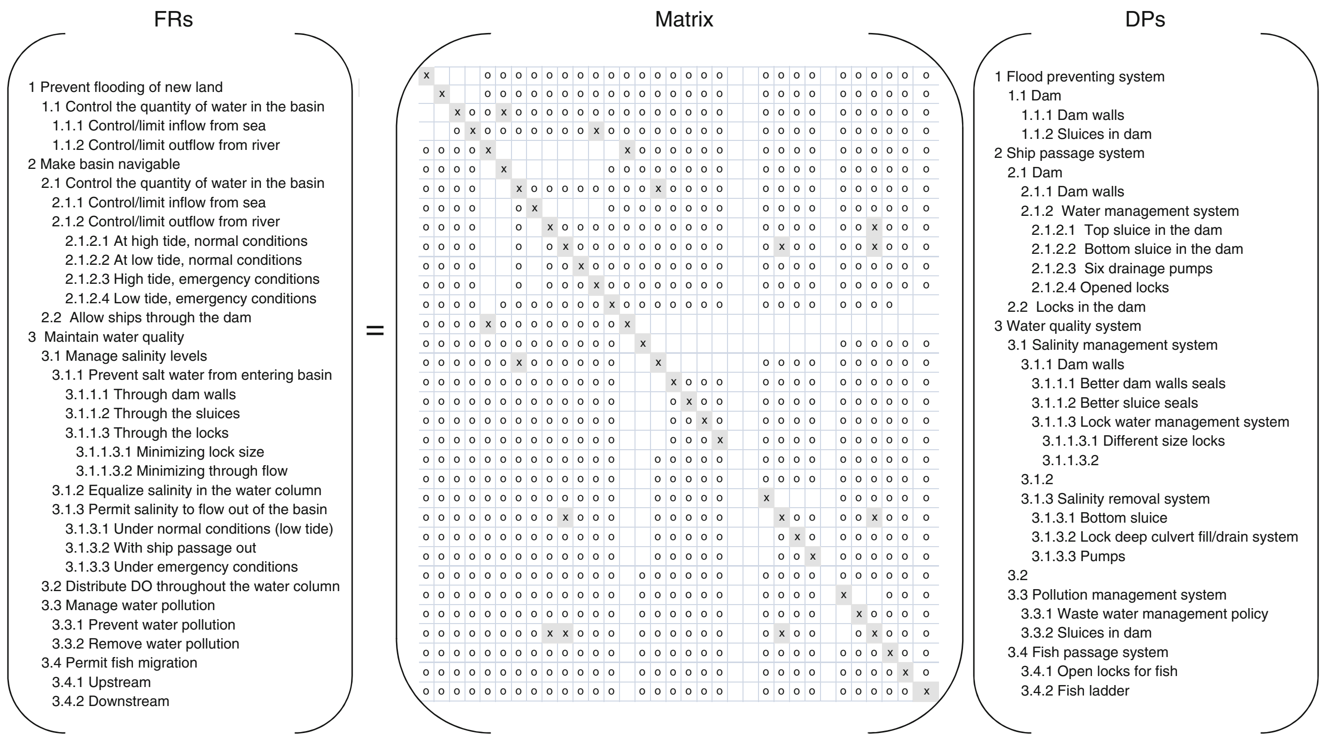

Fig. 4 Design matrix for the old Charles River Dam

The design parameters which represent the artificial destratification system were removed from the final design matrix. The design parameter that dictates that all harbor water in the locks be pumped back into the harbor was also removed since this procedure is often not possible.

In addition, the fish migration section was expanded to cover both upstream and downstream migration. Downstream migration is still primarily achieved through the fish ladder. However, upstream migration relies more heavily on the passage of ships through the locks or on lock operators opening the locks specifically for the fish [40].

However, many of these benefits involved the removal of problems associated with pollution and the tidal mud flats. The dam, itself, only performed a handful of functions.

The primary function of the dam was to stabilize and control the quantity of water in the basin. This was achieved by the presence of the dam walls and the drainage sluices in the dam. In the process, the height of the surrounding land and the depth of the river had to be increased. This portion of the design matrix is decoupled (Fig. 4).

The designers were aware of the functions associated with the tides and of the effect that their removal would have on the basin. However, they expected the impact of the salt water intrusion to be much smaller than it actually was. As a result, the designers made a conscious, rational decision not to include features in the first.

7 Results

Formal design theories provide a number of ways to judge the quality of a design including: the presence or absence of coupling, the presence or absence of conflict, and changes in information content, complexity, and ideality.

7.1 No Conflict in the Design Matrices

All four of the design matrices shown are coupled; however there is no potential for conflict in the matrices. All of the coupled functions are coupled in the same way and in the same direction. Improving one would automatically improve the other. Disturbing one would automatically disturb the other. Thus, the coupling adds minimal complexity and does not negatively impact the probability of success of the design. All three of the designs shown were equally acceptable from this perspective.

7.2 Increased Probability of Success

The salt wedge is a time dependent phenomenon. It decreases with rainfall and increases with boat traffic. Thus, the salt wedge is smallest in the spring and largest in July and August.

The improvement to DP 211 which minimizes the salt water intrusion in the basin is an improvement in time. The better the design, the longer it takes for the salt wedge to occupy the basin. Thus, the improved design of the second Charles River Dam increased the percentage of time when the system was "successful" (i.e. exhibited acceptable water quality characteristics.) This increased the overall probability of success of the system and its desirability according to Axiomatic Design Theory's Information Axiom.

7.3 Increased Constraints

The second Charles River Dam replaced the natural mixing action of the tides with an artificial destratification system in an attempt to satisfy the functional requirements related to water quality that were present in the original tidal system. In many ways, it was a good design decision.

Once the first Charles River Dam was constructed, it could not be demolished. Route 28 is a six lane divided highway where it crosses the old Charles River Dam between Boston and Cambridge. In addition, the Boston.

Museum of Science is built on top of the old dam. Thus, a design solution which re-introduced the tides into the basin was impossible. Instead, the designers attempted to create a solution that would "satisfice" [42].

And for a time, they succeeded. The bubblers performed their intended functions with few negative side effects. In addition, the bubblers introduced little coupling into the system and caused no conflict. For 7 years, they performed admirably in a corrosive and caustic environment.

7.4 Increased Complexity, Decreased Ideality

Ultimately, all technical systems are subject to entropy and the ravages of time. Eventually, the bubbler system, the fish ladder, and the wet wells of the locks all began to fail and were partially or totally abandoned.

TRIZ's Law of Ideality explains this to some degree. The Law of Ideality states that "[i]deality always reflects the maximum utilization of existing resources, both internal and external to the system. The more free or readily available the resources utilized, the more ideal the system will be." When a design reaches its maximum state of ideality, the "mechanism disappears, while the function is performed" [43].

When the mechanism disappears, there is nothing to wear, break, or corrode. So minimizing the mechanism makes systems with long life spans more resistance to the effects of time. Thus, ideality is very important for technically complex systems or infrastructure.

In addition, ideality is important for socially complex systems or infrastructure. Someone has to pay for the construction, operation, and maintenance of all technical systems. If the funds come from the taxpayers, the popularity of the project will determine whether or not the project lives or dies.

The energy that mixed the water column in the original system was provided by the moon's gravitational pull at no cost to the designer (or the taxpayer). In contrast, the bubbler system which performed the same functions was expected to cost roughly $500,000 (June 1976 dollars) with an additional $25,000 per year for operation and maintenance [38]. Similarly, the fish ladder and wet wells required energy and maintenance to perform functions that were unnecessary when the dam did not exist.

These elements could have been repaired. The decision not to repair them was an economic decision. If the system had been more ideal and the overall costs had been lower, perhaps these elements would still be functioning.

8 Implications for Life Cycle Planning

This work has a number of implications for the life cycle planning of large complex systems and infrastructure. In particular:

- "Cradle to grave" takes on a different meaning, as it may not always be possible to remove decommissioned designs. Thus, both the new and discarded system may occupy the same physical location at different times
- The expected life of the system is much longer than consumer products, thus all time scales associated with the design are lengthened
- Demands on the designer for more functions and fewer side effects will increase with time, making it increasingly difficult for a static design to satisfy its stakeholders
- Constraints on the designer will increase with time, making it more difficult to improve the design
- As more constraints are added, there is less and less opportunity to increase the ideality of the system
- Ideality and the reduction of complexity are increasingly important, as the longer time scales associated with the system increase the effects of entropy (wear, corrosion, deterioration, etc.) and long-term costs can be difficult to justify to the public

9 Conclusions

"Chaos was the law of nature; Order was the dream of man."
– Henry B. Adams

This paper is not a criticism of the design of the Lower Charles River Basin. Quite the opposite: the scientists, designers, and engineers associated with those civil works are the heroes of our story. Over the past century, their efforts and ingenuity turned a tidal cesspool into a beautiful, clean freshwater basin which is enjoyed by millions of people.

The first Charles River Dam helped to improve the quality of life for the local residents. The second Charles River Dam helped to improve the water quality in the basin with no removal or replacement of functions from the original dam. When the functions performed by the tides were lost, they were replaced with artificial alternatives. When functional requirements were neglected, it was done deliberately and after much consideration.

The designers generally obeyed the first and second axioms of Axiomatic Design Theory. There was no serious conflict in the designs. And the second dam demonstrated increased ideality over the first by increasing the useful effects of the dam while decreasing the negative effects.

When aspects of the second design ceased to work, it was due more to the long term effects of entropy than a failure on the part of the designer. Thus, the designers were not defeated by a poor understand of design – but rather by the innate complexity of the problem that they were trying to solve and the chaotic environment in which their design had to function.

Indeed, the efforts of the designers' successors have not ceased. Today there are still discussions about how to implement more "ideal" artificial destratification systems in the basin. Scientists, both professionals and volunteers, are still actively studying the basin. Devoted lock operators are still manually shunting migratory fish through the locks. They dream of an orderly future with cleaner water for everyone.

This paper was part of a larger effort to explore how formal design methodologies can be used in the field of Civil and Environmental Engineering and what that field can teach us about design. It was shown that two formal design theories (Axiomatic Design and TRIZ) were able to help explain the successes, failures and evolution of the Charles River Dam in Boston, Massachusetts It was shown that issues associated with complexity, ideality, and constraints increase with time scale, making both the technical and social ideality of technical solutions to long-term problems of paramount concern.

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Rethinking the Role of Time in Formal Design Theories

M.K. Thompson and M.A. Doroshenko

Abstract All designers and all designs exist and operate in a world with time. It influences all that we create and all that we do. Yet, the role of time in many formal design theories has not been adequately addressed. This work explores some of the issues associated with coupling and conflict in time in formal design theories. The current treatment of time, coupling, and conflict in three formal design theories is reviewed. Different types of time varying designs and time-dependent conflict and coupling are discussed. Seven important characteristics of time-dependent conflict are identified. Finally, a number of options for incorporating time into the conceptual design matrix are presented and their relative merits are discussed.

Keywords Time · Coupling · Conflict · Design matrix

1 Introduction

All designers and all designs exist and operate in a world with time. It influences all that we create and all that we do. Yet, the role of time in many formal design theories has not been adequately addressed. This work explores some of the issues associated with coupling and conflict in time in formal design theories. The treatment of time, coupling and conflict in design matrices is explored in detail and several suggestions for modifying the traditional design matrix to accommodate time-varying systems are presented.

2 Time in Formal Design Theories

2.1 Time in Axiomatic Design Theory

Time is formally addressed in several aspects of Axiomatic Design (AD) Theory, most notably in the discussion of system design [1, 2]. In his book Axiomatic Design: Advances and Applications, Suh distinguishes between fixed systems where the "system has to satisfy the same set of functional requirements at all times and whose components do not change as a function of time" and flexible systems which "must be able to reconfigure [themselves] to satisfy different subsets of FRs throughout [their lives]." Module-junction diagrams and flow diagrams are proposed as alternatives to the design matrix to represent large, flexible systems in time.

AD acknowledges that the system range of a given design can drift or change with time. The tolerances of parts change over time due to damage, wear, creep, and other phenomena. Environmental conditions (weather, vibration, etc.) can also introduce time dependent variance into a system. Suh urges designers to make their designs more "robust" or "immune" to variation by decreasing the stiffness of the design, i.e. by making the design range of the system as large as possible.

Time is given additional consideration in Suh's Complexity Theory where he defines two types of time-dependent complexity: combinatorial complexity and periodic complexity. He stresses that combinatorial complexity can lead to chaotic behaviour in systems, and should be transformed into periodic complexity whenever possible. However, there are no examples of time dependent design matrices in the Axiomatic Design literature and no discussion of temporal coupling.

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2.2 Time in TRIZ

Time is considered in a number of elements in TRIZ. The Law of Ideality states that "any technical system throughout its lifetime tends to become more reliable, simple, effective – more ideal. Every time we improve a technical system, we nudge that system closer to Ideality" [3].

Altshuller also distilled eight patterns or lines related to the evolution of technical systems: life cycle, dynamization, multiplication cycle, transition from macro to micro, synchronization, scaling up or down, uneven development of parts, and automation [3].

The 40 Principles take into account time. Orloff says that nine of TRIZ's 40 Principles as related to the fundamental transform of separation in time: 2 (preliminary action), 7 dynamization), 8 (periodic action), 18b (mediator), 28 (previously installed cushions), 33 (quick jump), 35b unite), 39 (preliminary counter action), and 40 (uninterrupted useful function). Principles 15 (discard and renewal of parts) and 36 (feedback) also acknowledge the need to address changes in the design over time.

In particular, principles #7, #8, #13 (inexpensive short life object as a replacement for expensive long-life one), and #15 (discard and renewal of parts) are related to periodicity. And principles 9 (preliminary anti-action), 10 (preliminary action), 13, 15, 18, 28, 30 (feedback), and 39 attempt to anticipate and address problems which may occur in the future [4]. (Note: Orloff's numbering of the 40 Principles is not the same as Altshuller's original order).

The TRIZ contradiction matrix lists 39 features which can either be improved or be degraded by various decisions made in the process of design. Included in this list are speed and loss of time [3, 4]. Finally, Orloff lists "temporal resources" (frequency, duration, order of events, etc.) as a subset of "physical-technical resources" in his reinvented version of TRIZ [4].

Despite all of this attention to the evolution and behaviour of systems in time, TRIZ does not include any formal tools for tracking the appearance and disappearance of conflicts in time.

2.3 Time in Other Design Theories

Time also appears in traditional engineering design, product design and other design fields. For example, Pahl and Beitz discuss the use of function structures in engineering design. These permit the designer to map the flow of resources (signals, materials, etc.) through the functions and thus can be used to order the functions in time [5].

3 Coupling and Conflict in Formal Design Theories

3.1 Coupling in Axiomatic Design Theory

The Independence Axiom of Axiomatic Design Theory encourages the designer to "maintain the independence of the functional requirements (FRs)" so that each of the FRs can "be satisfied without affecting the other FRs" [1]. Thus, it urges the designer to minimize all instances of coupling between FRs in the design matrix.

Avoiding coupling in design is important because it is sometimes difficult or impossible to predict the effect that one FR (or its associated design parameter) will have on the other FRs. In addition, it is difficult to predict whether the effect will be positive or negative. Thus, coupling in AD can be viewed as an attempt to avoid the potential for conflict.

AD permits the designer to indicate strong coupling in the design matrix by using a capital "X" and to indicate weak coupling by using a lowercase "x." This can be used to predict the impact of a conflict in the matrix. But it says nothing about the nature of the conflict itself.

3.2 Conflict in TRIZ

One of the fundamental tenets of TRIZ is the identification and resolution of contradictions or conflicts in the system. TRIZ identifies two types of contradiction: technical contradictions which are resolved using the 40 Principles and physical contradictions which are resolved using fundamental transformations [3].

Orloff has expanded the discussion of contradiction in TRIZ by developing six functional-structural models which describe the types of conflicts which can occur in a system. These include: opposition, double influence, self-harm, incompatible influences, influence on two objects, and ineffective influence [4]. But no issues associated with the nature of these contradictions in time are discussed.

3.3 Conflict in Traffic Systems

Traditional traffic conflict analysis identifies four types of vehicle to vehicle conflicts: merging conflicts, diverging conflicts, crossing conflicts, and sequential or queuing conflicts [6]. These conflicts are usually overlaid on a road or intersection to show where traffic accidents are likely to occur. Figure 1 shows a typical four-way intersection with 16 crossing conflicts, 8 diverging conflicts and 8 merging conflicts.

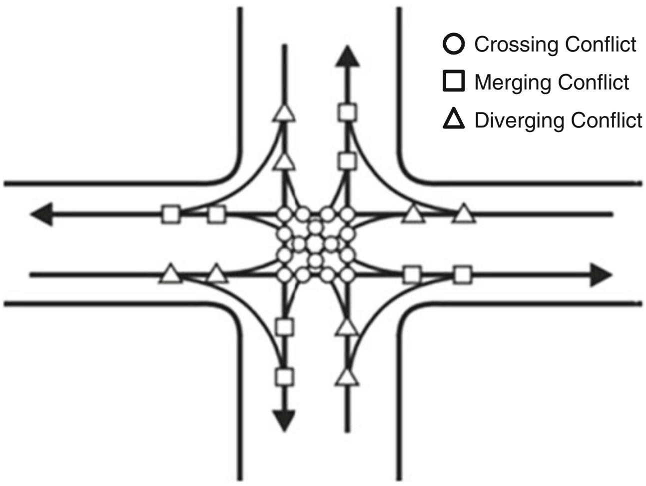

Fig. 1 Traffic conflict points in a typical four-way intersection [7]

Like Axiomatic Design Theory, traditional traffic conflict theory indicates the potential for conflict. In addition, it shows where the conflict is likely to take place and what type of conflict may occur. But it says nothing about when the conflict may occur and what impact that conflict might have on the larger transportation system.

4 Time Varying Systems

Technical artifacts can vary with time in three basic ways. First, the design itself may vary or be reconfigured with time as with Suh's flexible systems. Second, the environment in which the design functions may change. For example, in manufacturing and transportation systems, the demand and flow of objects through the system will vary with time. In both of these cases, the variation may happen over a relatively short period of time. Finally, the design may evolve with time. Computers may be upgraded. Modular systems may obtain additional features. Consumer products may be replaced with a newer model. This change typically happens over a longer period of time.

5 Coupling and Conflict in Time

Any variation in time can lead to coupling and conflict in time. That coupling can either be static, sequential or simultaneous.

5.1 Static Coupling

Since the functional requirements of a flexible design can vary with time, so can the coupled state of the design matrix. This type of coupling is static: these conflicts will remain in the system until the state of the system changes again. Thus, the designer must be responsible for identifying and eliminating coupling and conflict for each time step in the design.

5.2 Sequential Coupling

Sequential coupling occurs in situations where functions must be performed in a particular order. For example, clothes must be washed before they can be dried. Sequential coupling is observed in many fields, including computer science and transportation and logistics. However, neither Axiomatic Design Theory nor TRIZ adequately address sequential coupling.

Sequential coupling can occur in situations where no functional coupling is present. A washing machine is functionally (and physically) independent from a clothes dryer. But the functions that the two perform are still linked in time.

Since sequential coupling links various parts of a system in time, it permits cumulative problems in one part of the system to affect other parts of the system. Bottlenecks in manufacturing systems and traffic jams in transportation systems are both examples of how the effect of sequential coupling can snowball.

5.3 Simultaneous Coupling

Axiomatic Design advocates the physical integration of designs (i.e. combining different design parameters in the same physical object) as long as functional independence can be maintained. This is also consistent with TRIZ's Law of Ideality which advocates the use of free or hidden resources. However, physical integration can easily lead to simultaneous coupling if the functions associated with the integrated design parameters must be performed at the same time.

Integrated bottle/can openers are very common in household kitchens. The bottle opener is functionally independent from the can opener as long as one does not wish to open a bottle and a can at the same time. So this type of physical integration is rarely a problem. But if a cellular telephone uses the same port to charge the battery and to use the headset, it could quickly annoy the owner.

6 Characteristics of Time Dependent Conflict

Based on the discussion above, it is concluded that there are 7 characteristics of conflict in time that must be addressed:

- Whether or not the potential for conflict exists
- The location where conflict will occur
- The type(s) of conflict that will occur
- When the conflict will occur
- In what order the conflict will occur
- How that conflict will affect other aspects of the system
- If and when the conflict will disappear

It is the responsibility of the designer to understand the characteristics of the coupling and conflict within the system so they can attempt to eliminate it. It is the responsibility of the design researcher to provide tools to help the designer visualize the time-dependent system and to facilitate the resolution of conflict. One way to do this is to integrate time into the design matrix.

7 Time in the Design Matrix

7.1 Design Matrix for Flexible Systems

The most basic way to represent the changes in time of a flexible or evolving system is to construct a standard design matrix for each time step or period of time. Examples of this can be seen in our previous work related to the evolution of tidal dam systems [8, 9].

7.2 Design Matrix for Regular Periodic Systems Without Conflict

Flexible systems like the typical four-way intersection described above which exhibit regular periodic behavior can be represented with one design matrix per time step. Figure 2 shows four design matrices for a multi-lane alternating periodic intersection. In the first time step, north and southbound traffic is permitted to travel through the intersection. In the second time step, north and south-bound traffic is permitted to turn right, while east and west-bound traffic is permitted to turn left. The third and fourth time steps reverse the directions.

The design matrices in each step are uncoupled and there is no potential for conflict in the system as long as all vehicles obey the traffic signals.

7.3 Design Matrix for Regular Period Systems with Conflict

The previous example examined a multi-lane intersection where each traffic stream had a dedicated lane for travel. However, many two-lane four-way intersections do not have dedicated turn lanes. Figure 3 shows the design matrices for the smaller intersection.

In this case, each design matrix is fully coupled because in each time step, all traffic streams have the potential for a diverging conflict. Indicating the coupling with a “x” would provide no information to the designer. Instead, a hybrid design matrix [10] was constructed and the coupling was indicated by the traffic conflict symbol which represented the type of conflict that could occur. (The symbol for a crossing conflict was replaced with a “x” to reduce confusion).

These design matrices show that the potential for conflict exists, where the conflict will occur, and what types of

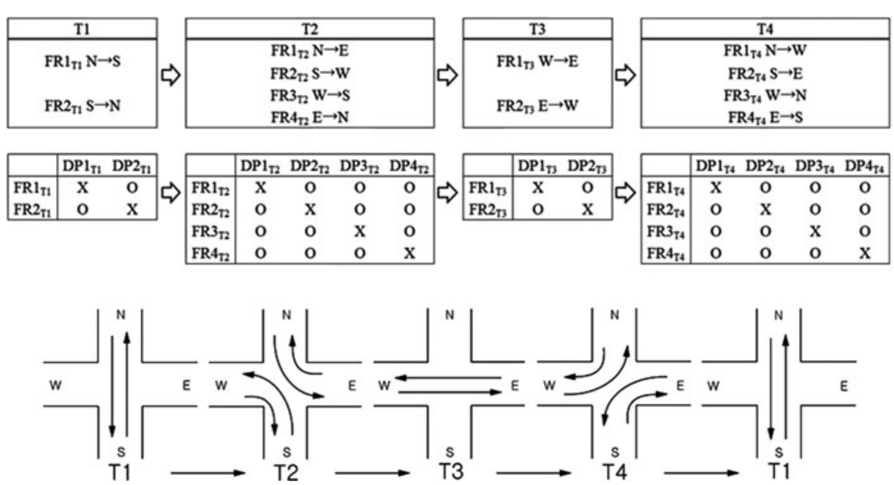

Fig. 2 Design matrices for a multi-lane periodic alternating intersection [10]

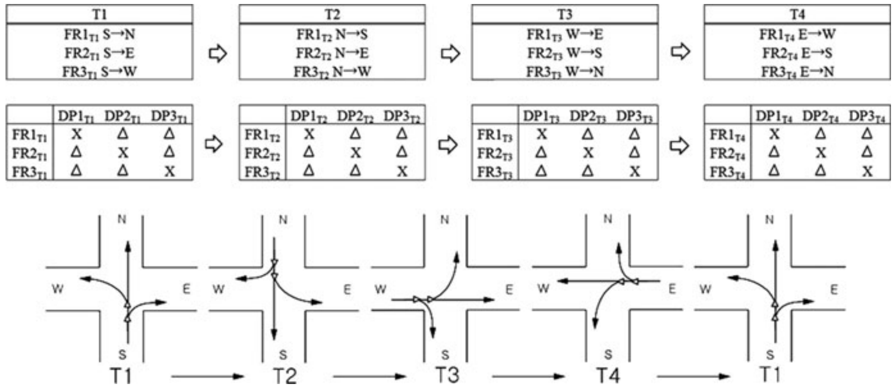

Fig. 3 Design matrices for a two-lane periodic alternating intersection [10]

conflict can occur but they cannot predict when a conflict will occur and whether or not a traffic accident will result.

7.4 Holistic Design Matrix for Systems with Irregular Sequential Coupling

Many intersections are not regulated by traffic signals. In addition, many intersections are strongly affected by rush hour traffic which has a period of hours, not minutes. These systems may be strongly affected by irregular or long-periodic time-varying sequential coupling.

Consider the following example of an unregulated intersection in Daejeon, South Korea (Fig. 4). Because the major highway is divided, a complicated series of underpasses and u-turns has been created to permit drivers to travel to and from all directions.

This system can be represented using a single, holistic hybrid design matrix (Fig. 5) which includes functional requirements and design parameters for all 16 origin-destination pairs in the intersection. Each entry of the design matrix represents one or more traffic conflicts which can occur. The physical location of each conflict is shown in Fig. 6.

Fig. 4 Google Earth view of a unregulated intersection

7.5 Modular Design Matrix for Systems with Irregular Sequential Coupling

Unfortunately the design matrix in Fig. 5 provides the designer with no information about the intersection in time. Instead, each sub-set of the intersection can be treated as a module (Fig. 7) and a modular hybrid design matrix can be constructed (Fig. 8). However, the cross-coupling is time dependent so the non-diagonal terms of the hybrid design matrix cannot be determined for all time.

Since the sequential relationship of each module in the intersection is fixed, both the locations of potential sequential conflict in the matrix and the order in which the conflict will occur are easily predicted. Figure 9 shows the order of sequential coupling in the intersection.

A “1” in a dark gray box indicates a location where conflict will first occur in the system when an adjacent module reaches its storage capacity of vehicles. A “2” in a medium gray box indicates second order coupling which will result when the roads associated with the first order conflict are also full. In this intersection, four levels of sequential conflict are possible.

Figure 9 does not show when a conflict will occur and when it will disappear. But it does show the order in which conflicts will occur and what their effect on neighbouring elements of the design will be.

7.6 Qualitative Modular Design Matrix

To show the progression of conflict in real time, it must be possible to distinguish between a state with potential

	DP1	DP2	DP3	DP4	DP5	DP6	DP7	DP8	DP9	DP10	DP11	DP12	DP13	DP14	DP15	DP16
FR1	X	△	△	△	⧄	⧄	O	□	O	□	O	⧄	O	O	□	O
FR2	△	X	△	△	O	O	□	O	□	O	O	O	O	O	O	□
FR3	△	△	X	△	X□	X	O	X	X	O	□	O	□	O	O	X
FR4	△	△	△	X	⧄	□	O	⧄	O	⧄	O	□	⧄	□	O	⧄
FR5	⧄	O	X□	⧄	X	△	△	△	X⧄	⊠	□	⊠	□	⧄	O	X⧄
FR6	⧄	O	X	□	△	X	△	△	X	⧄	O	□	⧄	□	O	X⧄
FR7	O	□	O	O	△	△	X	△	□	O	O	O	O	O	O	□
FR8	□	O	X	⧄	△	△	△	X	X	□	O	⧄	O	O	□	X
FR9	O	□	X	O	X⧄	X	□	X	X	△	△	△	⧄	O	O	□
FR10	□	O	O	⧄	⊠	⧄	O	□	△	X	△	△	⧄	O	□	⧄
FR11	O	O	□	O	□	O	O	O	△	△	X	△	□	O	O	⧄
FR12	⧄	O	O	□	⊠	□	O	⧄	△	△	△	X	⊠	□	O	⊠
FR13	O	O	□	⧄	□	⧄	O	O	⧄	⧄	□	⊠	X	△	△	△
FR14	O	O	O	□	⧄	□	O	O	O	O	O	□	△	X	△	△
FR15	□	O	O	O	O	O	O	□	O	□	O	O	△	△	X	△
FR16	O	□	X	⧄	X⧄	X⧄	□	X	□	⧄	⧄	⊠	△	△	△	X

Fig. 5 Hybrid design matrix for the unregulated intersection [11]

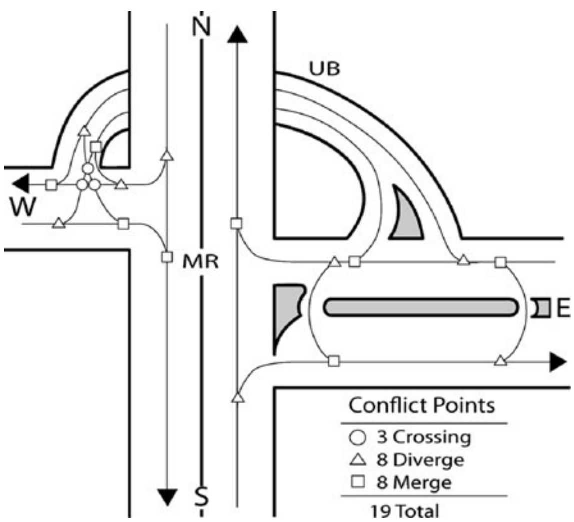

Fig. 6 Conflict points of the unregulated intersection [11]

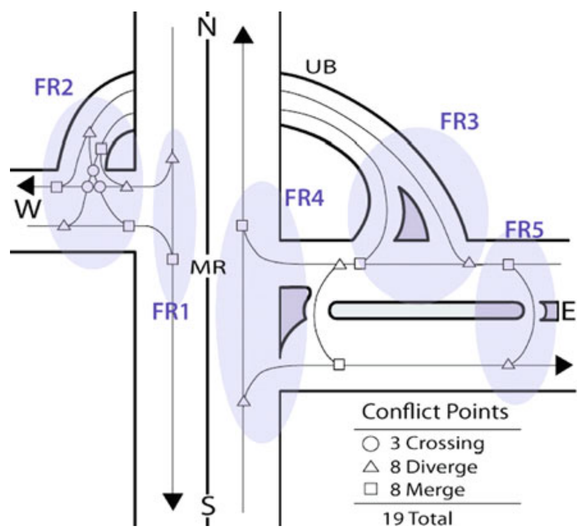

Fig. 7 Modules of the unregulated intersection [11]

coupling and one with coupling present. To do this, a qualitative modular design matrix can be constructed.

In Fig. 10, all of the potential conflict points are shown as empty circles with a number inside which represents the order of coupling. When the conflict occurs, the circle can be filled in to show its current state. The darker circles refer to the highest level FRs (1–5) and indicate that the whole module is affected by the current conditions. The gray circles indicate coupling in a sub-FR.

Figure 11 shows the state of the system when the northbound traffic on the main highway starts to interfere with Module 4. The diagonal terms associated with Module #4 are updated from "OK" to "JAM." In moments, the congestion spreads to Module #3 and six conflicts are added to the design matrix.

As traffic increases, vehicles that wish to traverse Module #3 begin to form a line down the hill and under the bridge. Soon Module #2 and Module #5 are affected (Fig. 12). The congestion in module 2 quickly starts to back up onto the south-bound highway, introducing conflict into Module #1 (Fig. 13).

7.7 Quantitative Modular Design Matrix

Thus far, conflict has been treated in only two possible states: true or false. But it is also possible to describe the progression of conflict in the design matrix numerically.

	DP1	DP11	DP12	DP13	DP2	DP21	DP22	DP23	DP24	DP25	DP26	DP3	DP31	DP32	DP33	DP4	DP41	DP42	DP43	DP44	DP5	DP51	DP52	DP53
FR1	X																							
FR11		X	Δ	□																				
FR12		Δ	X	O																				
FR13		□	O	X																				
FR2					X																			
FR21						X	Δ	□	X	X	O													
FR22						Δ	X	O	O	□	O													
FR23						□	O	X	Δ	O	O													
FR24						X	O	Δ	X	X	□													
FR25						X	□	O	X	X	Δ													
FR26						O	O	O	□	Δ	X													
FR3												X												
FR31													X	□	O									
FR32													□	X	Δ									
FR33													O	Δ	X									
FR4																X								
FR41																	X	Δ	□	O				
FR42																	Δ	X	O	□				
FR43																	□	O	X	Δ				
FR44																	O	□	Δ	X				
FR5																					X			
FR51																						X	Δ	O
FR52																						Δ	X	□
FR53																						O	□	X

Fig. 8 Modular hybrid design matrix of the unregulated intersection [11]

	DP1	DP11	DP12	DP13	DP2	DP21	DP22	DP23	DP24	DP25	DP26	DP3	DP31	DP32	DP33	DP4	DP41	DP42	DP43	DP44	DP5	DP51	DP52	DP53
FR1	X				X							X				X					X			
FR11		x	△	□	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
FR12		△	x	o	1	o	o	o	o	1	1	2	2	o	o	3	o	o	3	3	4	4	4	o
FR13		□	o	x	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
FR2	X				X							X				X					X			
FR21	1	o	o	1		x	△	□	X	X	o	o	o	o	o	o	o	o	o	o	o	o	o	o
FR22	o	o	o	o		△	x	o	o	□	o	o	o	o	o	o	o	o	o	o	o	o	o	o
FR23	1	o	o	1		□	o	x	△	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
FR24	o	o	o	o		X	o	△	x	X	□	1	1	o	o	2	o	o	2	2	3	3	3	o
FR25	o	o	o	o		X	□	o	X	x	△	o	o	o	o	o	o	o	o	o	o	o	o	o
FR26	o	o	o	o		o	o	o	□	△	x	1	1	o	o	2	o	o	2	2	3	3	3	o
FR3	X				X							X				X					X			
FR31	o	o	o	o	o	o	o	o	o	o	o		x	□	o	1	o	o	1	1	2	2	2	o
FR32	o	o	o	o	o	o	o	o	o	o	o		□	x	△	1	o	o	1	1	2	2	2	o
FR33	2	o	o	2	1	1	1	o	o	o	o		o	△	x	o	o	o	o	o	o	o	o	o
FR4	X				X							X				X					X			
FR41	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o		x	△	□	o	o	o	o	o
FR42	4	o	o	4	3	3	3	o	o	o	o	2	o	2	2		△	x	o	□	1	1	1	o
FR43	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o		□	o	x	△	o	o	o	o
FR44	4	o	o	4	3	3	3	o	o	o	o	2	o	2	2		o	□	△	x	1	1	1	o
FR5	X				X							X				X					X			
FR51	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o		x	△	o
FR52	3	o	o	3	2	2	2	o	o	o	o	1	o	1	1	2	o	o	2	2		△	x	□
FR53	3	o	o	3	2	2	2	o	o	o	o	1	o	1	1	2	o	o	2	2		o	□	x

Fig. 9 Modular hybrid design matrix of the unregulated intersection with order-dependent cross-coupling

	DP1	DP11	DP12	DP13	DP2	DP21	DP22	DP23	DP24	DP25	DP26	DP3	DP31	DP32	DP33	DP4	DP41	DP42	DP43	DP44	DP5	DP51	DP52	DP53
FR1	X				X							X				X					X			
FR11		OK	△	□	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
FR12		△	OK	○	①	○	○	○	○	①	①	②	②	○	○	③	○	○	③	③	④	④	④	○
FR13		□	○	OK	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
FR2	X				X							X				X					X			
FR21	①	○	○	①		OK	△	□	X	X	○	○	○	○	○	○	○	○	○	○	○	○	○	○
FR22	○	○	○	○		△	OK	○	○	□	○	○	○	○	○	○	○	○	○	○	○	○	○	○
FR23	①	○	○	①		□	○	OK	△	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
FR24	○	○	○	○		X	○	△	OK	X	□	①	①	○	○	②	○	○	②	②	③	③	③	○
FR25	○	○	○	○		X	□	○	X	OK	△	○	○	○	○	○	○	○	○	○	○	○	○	○
FR26	○	○	○	○		○	○	○	□	△	OK	①	①	○	○	②	○	○	②	②	③	③	③	○
FR3	X				X							X				X					X			
FR31	○	○	○	○	○	○	○	○	○	○	○		OK	□	○	①	○	○	①	①	②	②	②	○
FR32	○	○	○	○	○	○	○	○	○	○	○		□	OK	△	①	○	○	①	①	②	②	②	○
FR33	②	○	○	②	①	①	①	○	○	○	○		○	△	OK	○	○	○	○	○	○	○	○	○
FR4	X				X							X				X					X			
FR41	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○		OK	△	□	○	○	○	○	○
FR42	④	○	○	④	③	③	③	○	○	○	○	②	○	②	②		△	OK	○	□	①	①	①	○
FR43	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○		□	○	OK	△	○	○	○	○
FR44	④	○	○	④	③	③	③	○	○	○	○	②	○	②	②		○	□	△	OK	①	①	①	○
FR5	X				X							X				X					X			
FR51	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○		OK	△	○
FR52	③	○	○	③	②	②	②	○	○	○	○	①	○	①	①	②	○	○	②	②		△	OK	□
FR53	③	○	○	③	②	②	②	○	○	○	○	①	○	①	①	②	○	○	②	②		○	□	OK

Fig. 10 Qualitative modular design matrix of the unregulated intersection with time dependent cross coupling (no conflict present)

	DP1	DP11	DP12	DP13	DP2	DP21	DP22	DP23	DP24	DP25	DP26	DP3	DP31	DP32	DP33	DP4	DP41	DP42	DP43	DP44	DP5	DP51	DP52	DP53
FR1	X				X							X				X					X			
FR11		OK	△	□	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
FR12		△	OK	○	①	○	○	○	○	①	①	②	②	○	○	③	○	○	③	③	④	④	④	○
FR13		□	○	OK	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
FR2	X				X							X				X					X			
FR21	①	○	○	①		OK	△	□	X	X	○	○	○	○	○	○	○	○	○	○	○	○	○	○
FR22	○	○	○	○		△	OK	○	○	□	○	○	○	○	○	○	○	○	○	○	○	○	○	○
FR23	①	○	○	①		□	○	OK	△	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
FR24	○	○	○	○		X	○	△	OK	X	□	①	①	○	○	②	○	○	②	②	③	③	③	○
FR25	○	○	○	○		X	□	○	X	OK	△	○	○	○	○	○	○	○	○	○	○	○	○	○
FR26	○	○	○	○		○	○	○	□	△	OK	①	①	○	○	②	○	○	②	②	③	③	③	○
FR3	X				X							X				X					X			
FR31	○	○	○	○	○	○	○	○	○	○	○		JAM	□	○	❶	○	○	❶	❶	②	②	②	○
FR32	○	○	○	○	○	○	○	○	○	○	○		□	JAM	△	❶	○	○	❶	❶	②	②	②	○
FR33	②	○	○	②	①	①	①	○	○	○	○		○	△	OK	○	○	○	○	○	○	○	○	○
FR4	X				X							X				X					X			
FR41	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○		JAM	△	□	○	○	○	○	○
FR42	④	○	○	④	③	③	③	○	○	○	○	②	○	②	②		△	N/A	○	□	①	①	①	○
FR43	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○		□	○	JAM	△	○	○	○	○
FR44	④	○	○	④	③	③	③	○	○	○	○	②	○	②	②		○	□	△	JAM	①	①	①	○
FR5	X				X							X				X					X			
FR51	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○		OK	△	○
FR52	③	○	○	③	②	②	②	○	○	○	○	①	○	①	①	②	○	○	②	②		△	OK	□
FR53	③	○	○	③	②	②	②	○	○	○	○	①	○	①	①	②	○	○	②	②		○	□	OK

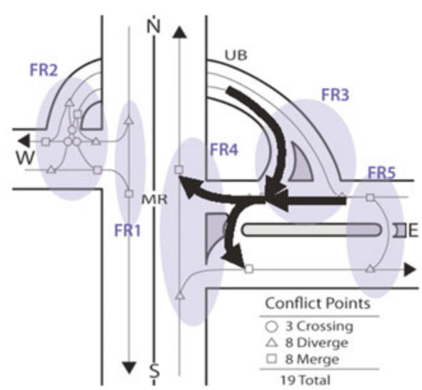

Fig. 11 Conflict caused by a light traffic jam

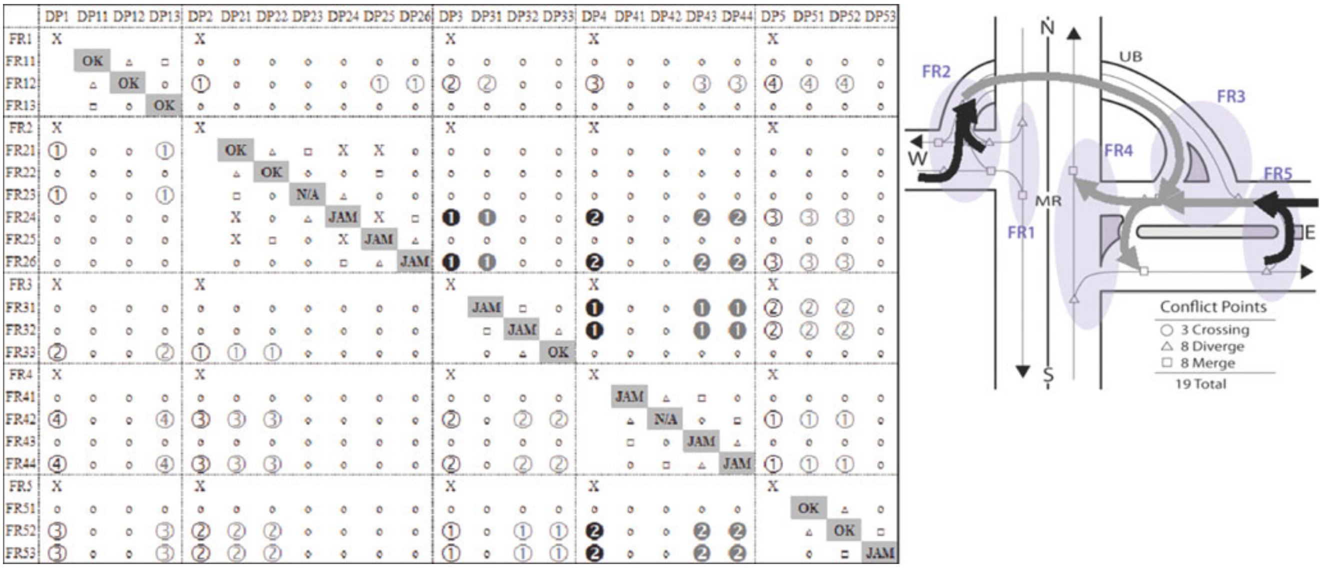

Fig. 12 Conflict increases as the traffic jam progresses

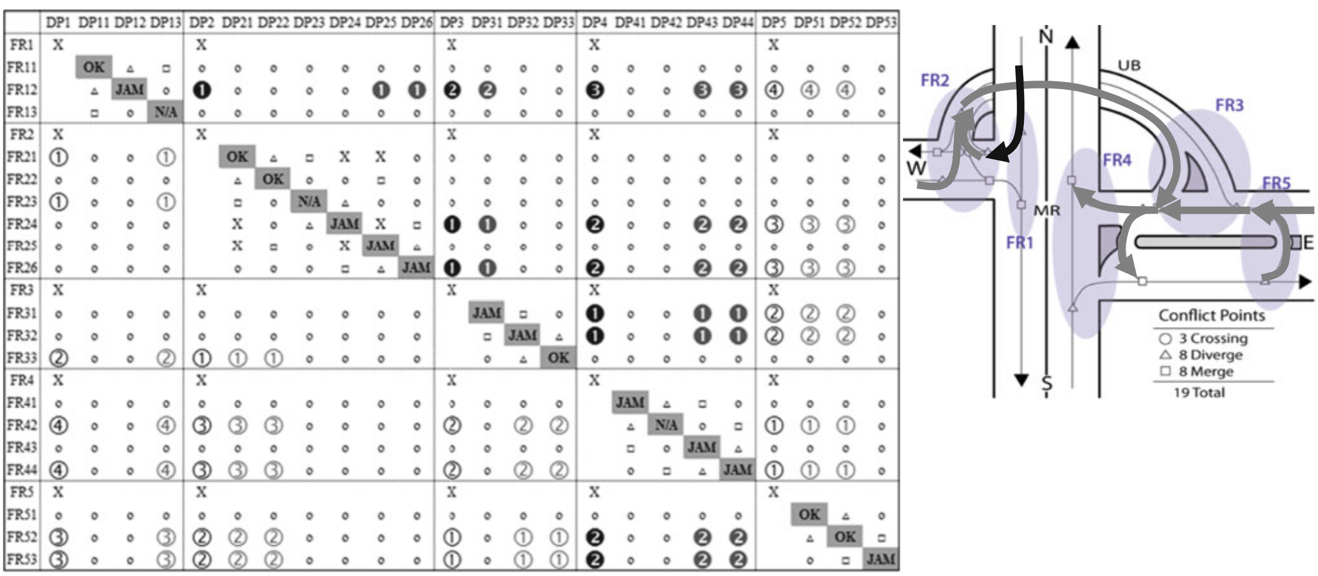

Fig. 13 Conflict spreads to the furthest point in the intersection

A quantitative modular design matrix can be constructed to show how the input conditions affect specific aspects of the system. Unlike a traditional design matrix where each element of the design matrix represents the relationship between the FR and DP, the time-dependent modular design matrix represents the current rate flow rate into a given section.

Figure 14 shows a reduced quantitative modular design matrix during light traffic conditions. In this case, there are roughly 2,340 cars per hour travelling northbound on the major highway. There are 444 cars per hour travelling southbound on the same road. 396 cars per hour enter the intersection from the west. These are added to 144 cars per hour which re-enter the intersection from the north. Most of these cars (540 per hour) head north through modules #3 and #4 (Fig. 15). There are no conflicts at point "Z" when traffic is light.

Under heavy traffic conditions, the north-bound flow increases 60% to 3,780 cars per hour. Point "Z" becomes a point of conflict and cars from FR31 are unable to enter Module #4 without delay (Figs. 16 and 17).

Figures 18 and 19 show the differences in system performance between the light and heavy traffic cases. The increased traffic in FR41 has caused decreases in throughput in most of the other modules in the system.

Fig. 14 Quantitative modular design matrix for light traffic

	DP1	DP11	DP12	DP13	DP2	DP21	DP22	DP23	DP24	DP25	DP26	DP3	DP31	DP32	DP33
FR1	X				X							X			
FR11		**2364**	Δ	□	o	o	o	o	o	o	o	o	o	o	o
FR12		Δ	**444**	o	**444**	o	o	o	o	**300**	**144**	**144**	**144**	o	o
FR13		□	o	**20**	o	o	o	o	o	o	o	o	o	o	o
FR2	X				X							X			
FR21	**0**	o	o	**0**		**0**	Δ	□	X	X	o	o	o	o	o
FR22	o	o	o	o		Δ	**96**	o	o	□	o	o	o	o	o
FR23	**20**	o	o	**20**		□	o	**20**	Δ	o	o	o	o	o	o
FR24	o	o	o	o		X	o	Δ	**396**	X	□	**396**	**396**	o	o
FR25	o	o	o	o		X	□	o	X	**300**		o	o	o	o
FR26	o	o	o	o		o	o	o	□	Δ	**144**	**144**	**144**	o	o
FR3	X				X							X			
FR31	o	o	o	o	o	o	o	o	o	o	o		**540**	□	o
FR32	o	o	o	o	o	o	o	o	o	o	o		□	**130**	Δ
FR33	**0**	o	o	**0**	**96**	**0**	**96**	o	o	o	o		o	Δ	**96**

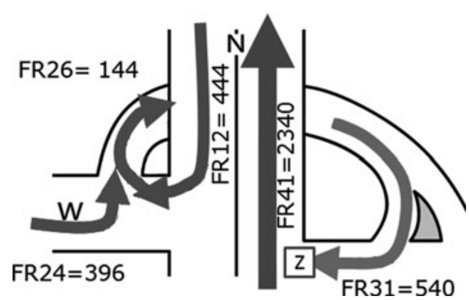

Fig. 15 Traffic flows through the intersection for light traffic conditions

Fig. 16 Quantitative modular design matrix for heavy traffic

	DP1	DP11	DP12	DP13	DP2	DP21	DP22	DP23	DP24	DP25	DP26	DP3	DP31	DP32	DP33
FR1	X				X							X			
FR11		**3276**	Δ	□	o	o	o	o	o	o	o	o	o	o	o
FR12		Δ	**216**	o	**216**	o	o	o	o	**96**	**120**	**120**	**120**	o	o
FR13		□	o	**24**	o	o	o	o	o	o	o	o	o	o	o
FR2	X				X							X			
FR21	**0**	o	o	**0**		**0**	Δ	□	X	X	o	o	o	o	o
FR22	o	o	o	o		Δ	**120**	o	o	□	o	o	o	o	o
FR23	**24**	o	o	**24**		□	o	**24**	Δ	o	o	o	o	o	o
FR24	o	o	o	o		X	o	Δ	**300**	X	□	**300**	**300**	o	o
FR25	o	o	o	o		X	□	o	X	**96**	Δ	o	o	o	o
FR26	o	o	o	o		o	o	o	□	Δ	**120**	**120**	**120**	o	o
FR3	X				X							X			
FR31	o	o	o	o	o	o	o	o	o	o	o		**420**	□	o
FR32	o	o	o	o	o	o	o	o	o	o	o		□	**84**	Δ
FR33	**0**	o	o	**0**	**120**	**0**	**120**	o	o	o	o		o	Δ	**120**

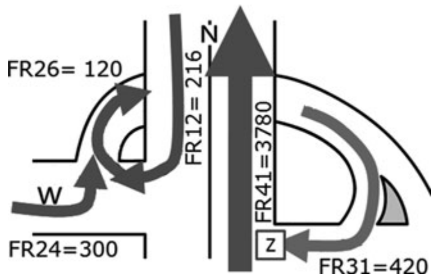

Fig. 17 Traffic flows through the intersection for heavy traffic conditions

Fig. 18 Difference in throughput for light and heavy traffic cases

	DP1	DP11	DP12	DP13	DP2	DP21	DP22	DP23	DP24	DP25	DP26	DP3	DP31	DP32	DP33
FR1	X				X							X			
FR11		**+3276**	Δ	□	o	o	o	o	o	o	o	o	o	o	o
FR12		Δ	**–228**	o	**–228**	o	o	o	o	**–204**	**–24**	**–24**	**–24**	o	o
FR13		□	o	**+4**	o	o	o	o	o	o	o	o	o	o	o
FR2	X				X							X			
FR21	**0**	o	o	**0**		**0**	Δ	□	X	X	o	o	o	o	o
FR22	o	o	o	o		Δ	**+24**	o	o	□	o	o	o	o	o
FR23	**+4**	o	o	**+4**		□	o	**+4**	Δ	o	o	o	o	o	o
FR24	o	o	o	o		X	o	Δ	**–96**	X	□	**–96**	**–96**	o	o
FR25	o	o	o	o		X	□	o	X	**–204**	Δ	o	o	o	o
FR26	o	o	o	o		o	o	o	□	Δ	**–24**	**–24**	**–24**	o	o
FR3	X				X							X			
FR31	o	o	o	o	o	o	o	o	o	o	o		**–120**	□	o
FR32	o	o	o	o	o	o	o	o	o	o	o		□	**–46**	Δ
FR33	**0**	o	o	**0**	**+24**	**0**	**+24**	o	o	o	o		o	Δ	**+24**

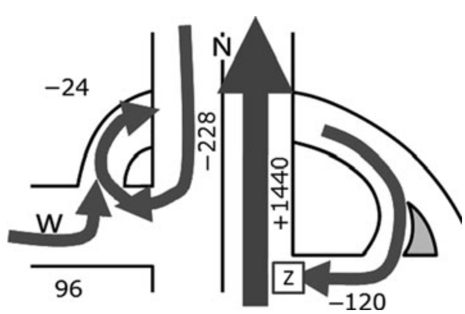

Fig. 19 Differences in traffic flows through the intersection between light and heavy traffic conditions

Through these examples, it is clear that the quantitative hybrid design matrix is able to convey all seven characteristics of the time-dependent conflict in this system.

8 Conclusions

This work has discussed both the importance and inadequate attention that has been paid to the role of time in formal design theories, especially in relation to coupling and conflict. Different types of time varying designs and time-dependent conflict and coupling were discussed. Seven important characteristics of time-dependent conflict were identified and a number of options for incorporating time into the conceptual design matrix were presented.

All of the options presented had both advantages and disadvantages, but only the quantitative hybrid design matrix was able to clearly relate all seven characteristics to the designer.

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Semantic Knowledge Based Approach for Product Maintenance Support

I. Sanya, E. Shehab, R. Roy, O. Houseman, and M. Jonik

Abstract The purpose of this chapter is to use semantic technology to represent the knowledge for product maintenance. Companies are beginning to understand the importance of utilising an effective approach to manage existing knowledge in order to increase their intellectual capital. However, one of the main constraints that have hindered the solution in resolving technical problems has been the efficient access to expertise. Therefore, there is need for enhancing the management and maintenance of knowledge through a semantic based approach. This research project adopts a qualitative research approach and a five-phase research methodology. This research project has highlighted that semantic technology enhances the reusability, flexibility and maintainability of knowledge and its management.

Keywords Semantics · Ontologies · Concepts · Rules · Knowledge representation

1 Introduction

The management of knowledge is now quickly becoming an important business activity for many companies as they realise that in order to remain competitive, there is need for effectively managing intellectual resources. However, there is lack of "linguistics" within the way conventional systems communicate and companies are beginning to realise the importance of "semantics" within IT systems.

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For this reason, the theme of this research project will focus on identifying and developing a prototype application that adopts the use of semantic technology for knowledge management purposes. The semantic based prototype involves the transformation of an existing validated manual for bicycle diagnosis repair. The outcome of this research project is the representation of this manual embedded within a semantic based application for product maintenance support.

The capture of complex knowledge and maintenance diagnosis has always been an essential factor that has contributed to the success of companies as they realise that their most valuable resource is the knowledge of its people. However, one of the main constraints that have hindered the solution in resolving technical problems has been the efficient access to knowledge and expertise due to experts that are bounded by their geographical location or the sudden departure of subject matter experts. As a result of this, current engineers end up spending large amount of time to find a solution to previously resolved problems.

This leads to increased time-to-fix, downtime, and substantial unnecessary cost increase. A potential solution to this problem is the use of a knowledge based system which will reproduce knowledge from human experts utilising latest technologies such as semantics, declarative rules and ontologies.

A prototype demonstrator is then needed that will quantify the use of semantic technology within this field. A common solution has been the use of knowledge based systems which allows for knowledge reproduction. However, current knowledge based systems lacks meaning in communication which means a more efficient and effective way is needed for managing and maintaining knowledge in order to correct defects and improve system performance.

Thus, the main aim of this research project is to develop a prototype tool that will utilise semantic technology for the management and maintenance of knowledge in order to demonstrate and quantify the capability of this technology within the defence equipment support market.

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2 Related Literature

In today's world, any discussion of knowledge leads to understanding how knowledge is defined. In practice, knowledge is defined as starting at data, encompassing information and ending at knowledge. According to Grover and Davenport [1], knowledge is known to have the highest value in human contribution. It is the greatest relevance to making decisions and actions and it is also the most difficult content type to manage because it exists in people's mind tacitly.

Thus, there is need for effective knowledge capture. The National Health Service [2] suggests that the main purpose of knowledge capture is to acquire an expert's decision making process in great detail so that someone else could repeat the same set of process and establish the same results/conclusions.

The National Health Service [2] furthermore suggests that one of the best ways to capture tacit knowledge is using one-to-one, face-to-face interviews with experts. However, Milton [3] suggests other effective techniques such as protocol generation technique which is used to establish a record of behaviour, protocol analysis technique which is used for the identification of knowledge objects within a protocol and hierarchical techniques which is used to create, review and modify hierarchical knowledge in form of ladders.

O'Hara and Shadbolt [4] stated that the purpose of having so many knowledge elicitation techniques remains in the fact that experts possess various forms of tacit knowledge. It is essential to utilise the appropriate technique in order to access and capture the various types of knowledge. This process is referred to as the "differential access hypothesis" and has been implemented in real world settings with supporting evidence [3, 4].

Knowledge Based Systems are part of AI applications seeing as they emulate the "thinking processes" taken by humans in order to solve broad classes of problems [5]. Most research states that the main difference in which knowledge based systems differs from conventional systems is the approach taken to solve a problem. Conventional systems solve problems via algorithms, whereas KBS uses heuristics which is intended to increase the probability of solving a problem [6, 7]. The benefits of KBS has agreed by most authors includes time saving [7–9], quality improvement [7–10], applicability of practical knowledge [7, 8, 11] and consistency [7, 10, 11].

Furthermore, there has been vast amount of research within the area of computer based knowledge representation. It has been established that computers are a great way of storing and retrieving information. However, many have wondered about the current advancements with the science behind computer information [12].

Barski [12] argues that the scientist has not contributed enough in the world of knowledge representation and software and stated that the third revolution of computer's will be the era of the scientist which will allow computers to represent knowledge using integral calculus, theorem proving, linguistics (semantics), and other form of scientific distinct feature.

Furthermore, in today's world, the meaning of web content is not machine-accessible which means there is lack of semantics [13]. Semantics is defined as the study of meaning in communication. There is need for knowledge representation in semantics. Knowledge representation in semantics allows for the description of the problem domain, with concepts and the relations between those concepts. It allows for a shared agreement of meanings. All semantic based knowledge representation techniques must utilise "subject based classification". This is any form of content classification that groups objects by their subjects.

Semantic technology relies on the ontology model. This is a model that represents a set of concepts and the relationships between these concepts. This extends the subject based classification approaches due to its open vocabularies and open relationship types. The use of ontologies to represent complex knowledge has become common in government bodies such as NASA and UN [14].

More current advancements on semantic technology have occurred within the enterprise space. Semantic technology is used in order to integrate information and improve efficiency. Davies et al. [15] stated that BT's own fusion of billing and sales in one department has allowed for £2million annual savings and ongoing semantic innovation is being considered within this sector.

Davies et al. [15] suggested that companies such as Hakia, Siderean and Ontotext are carrying out underlying research within the area of semantic search. Also, within the area of information and process integration, there are companies such as Metatomix, Ontoprise and Radar Networks who just recently announced its "Twine semantic social networks offering".

Google also announced that it was changing the way in which search engines interpret words entered by users which highlights the importance of semantics [16].

Research has proved recently that semantic technology has been used within medical centres [17] and also within the financial Industry [18]. This type of technology is highly required within the defence equipment support market for the capture & maintenance of complex knowledge; however, semantic technology is not being utilised. This is where the weak links exists and the outcome of this research project will evaluate & validate the use of this technology within the defence equipment support market by developing an equipment diagnosis prototype as a demonstrator to quantify the use of semantic technology.

Many Researchers [19] argue that today's equipments incur high cost for maintenance due to its complexity. Therefore, it is necessary to enhance modern maintenance management systems. The conventional condition-based maintenance (CBM) is usually used to reduce maintenance activities and operates according to the indication of an equipment condition. Yam et al. [19] illustrates that a recent study of maintenance management practices demonstrates that the three major problems facing modern engineering plants are the reduction of high inventory cost for spare parts, pre-planning maintenance work for complex equipment under a complex environment and avoiding the risk of major failure and eliminating catastrophic circumstances that could occur to an equipment or system.

Fuchs et al. [20] supports the view of most researchers about the complexity of industrial systems and the need for highly capable maintenance systems for monitoring data. The key issue highlighted by this chapter suggests that there is lack of linguistics in representing and querying data from multiple sources.

The literature review has highlighted that there is lack of research projects focused on the application of semantic technology within maintenance support. Therefore, this research project has attempted to fill in this research gap by developing a semantic based prototype for this purpose.

3 Research Methodology

3.1 The Case Study Company

TechModal was founded in 2005 by PhD students researching semantic technology and cost engineering techniques within the aerospace sector. The company was formed to utilise the latest web technologies for practical solutions within decision support. Having researched the field of semantic technology at PhD level and implemented semantic technology applications in industry, TechModal have selected a world leading commercial semantic platform provider company known as Ontoprise as the most efficient framework on which to build semantic applications. Techmodal costing activities within the defence sector includes the Cost Capability Trade-Off, Value for Money Comparison (VFMC), Cost Benefit Analysis and Cost Effectiveness Analysis [21].

3.2 The Research Methodology

Figure 1 illustrates the adopted research methodology. The research project commenced with a familiarisation stage which clearly defined the project aim and objectives. An extensive literature review was used in order to identify research gaps and understand the review of literature cases on use of semantics and maintenance support. The output of this phase clearly identified the current use of semantics to manage and maintain knowledge. The second phase was for the researcher to undergo adequate training on the semantic platform proposed by the sponsoring company (Techmodal). Understanding how to utilise this semantic based application for the purpose of declaring concepts, rules and ontologies for a problem domain was essential in achieving the aim and objectives of the project. The output from this phase enhanced the researcher's familiarisation with the basics of developing a semantic based application for a specific problem domain. This stage was an ongoing activity seeing as new knowledge was discovered as the researcher continued to utilise the semantic based platform.

The platform known as SemanticGuide was developed by Ontoprise [22] and this platform has been utilised in this project. This platform is an ontology based intelligent advisory system which allows for knowledge automation. SemanticGuide [22] uses the idea of concepts which is referred to as the domain model ontology, rules (operational model ontology) and then an export mechanism to publish the application onto the web. This approach is used to model a problem domain.

The third phase was to capture and represent knowledge effectively using knowledge representation techniques such as UML (Unified Modelling Language) use case diagram and ontological knowledge representation techniques (Taxonomy). This phase also involved collecting and understanding the validated manual repair for a bicycle in order to transform this knowledge model into a semantic based platform.

The fourth phase was to develop the semantic based prototype. The development of this prototype established the key aspects and benefits of semantic technology Furthermore, the contribution to knowledge and application of results were identified.

Lastly, phase five validates the developed prototype and ensures the appropriate dissemination of the project results. The qualitative phenomenological study is an interesting study for this research project due to the fact that ontologies are used to model the semantic based prototype for the domain area and an ontology is described as the study of being and existence.

The quantitative approach was not adopted because the knowledge required has already been captured and validated within the Barnett's bicycle repair manual handbook. The qualitative approach enhanced the richness of what was being achieved and the researcher became subjectively immersed in the subject matter.

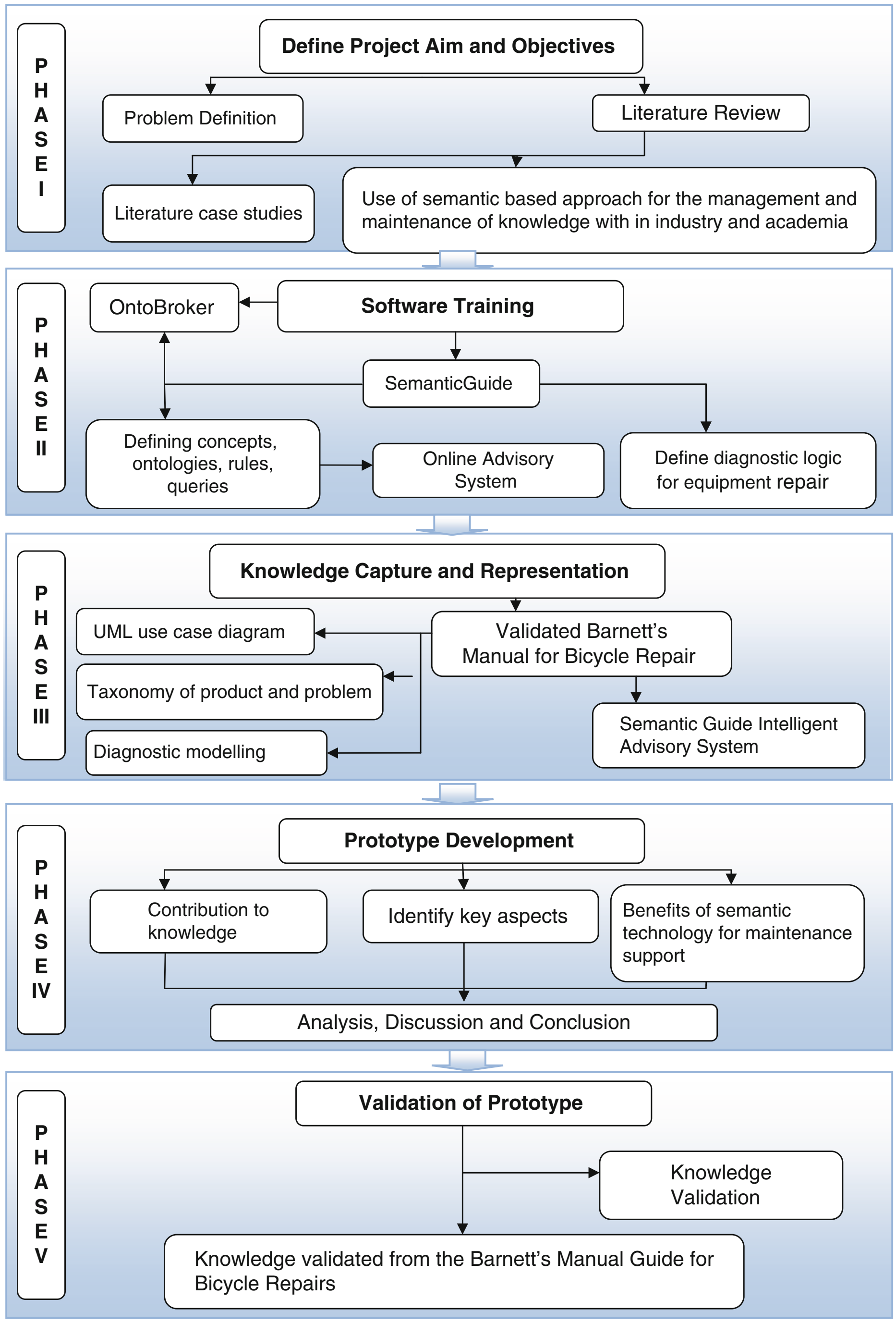

Fig. 1 Research programme methodology

4 The Prototype Development

After capturing and representing knowledge from the validated bicycle diagnosis repair, the semantic based prototype was developed using the semantic platform proposed by the sponsoring company. Semantic Guide uses the idea of rules, concepts and ontologies to model the problem domain.

4.1 Module 1: Maintenance Support

The development of the semantic based prototype for maintenance support commenced using SemanticGuide. Figure 2 illustrates the system architecture for SemanticGuide. This demonstrates that SemanticGuide has two types of system engineers. These are the knowledge engineer and knowledge editor. The knowledge engineer is responsible for

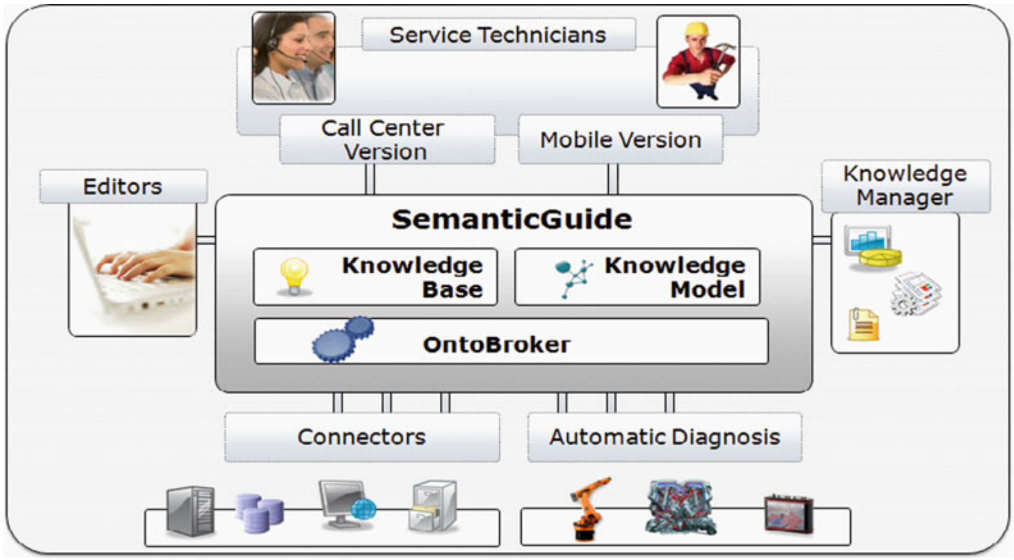

Fig. 2 Semanticguide architecture

structuring and developing the architecture of the knowledge base whilst the knowledge editor is responsible for adding and editing knowledge within the knowledge base. SemanticGuide can be deployed via a call centre version or a mobile version which is utilised by service technicians working underground in form of a PDA. SemanticGuide is also connected to various data sources such as oracle database for the knowledge base designer and Internet for web accessibility. SemanticGuide is composed of three core features. These are the knowledge base (rules declaration), the knowledge model which consists of an ontology for knowledge representation and OntoBroker which acts as the semantic middleware inference engine.

4.2 *Adopted Knowledge Management Approach*

In order to develop the semantic application, it was crucial to adopt a knowledge management approach. Firstly, the identification of concepts types/hierarchy with key individuals at the sponsoring company was established. This was achieved through group discussions and the outcome was the selection of the appropriate case study that will be utilised to demonstrate the semantic application. The bicycle domain was chosen due to the fact that a bicycle possess over 80 mechanical parts which at anytime could become faulty and in need of resolution diagnosis. The idea is that if the semantic application could successful model a bicycle domain, it could then be useful for a more complex domain such as an aircraft.

The next stage was to acquire the experts' knowledge on bicycle maintenance. The experts' knowledge was in form of a repair manual for bicycles. This was developed by a group of experts within the domain. The advantage of utilising this manual as the basis of the application is that the knowledge represented within it has already been validated. This helped in ensuring that the semantic model contains validated knowledge.

Furthermore, UML use case diagrams and ontological knowledge representation techniques were used to model various aspects of the domain before the prototype development as explained later during this chapter.

4.2.1 Define Knowledge Area

Defining a knowledge area is the responsibility of the knowledge manager. A knowledge area consists of concept product and problem. A concept bicycle was defined. The concept hierarchy was also defined seeing as different types of bicycles exist (road, mountain, BMX, etc). Furthermore, problems such as noise, chain failure, flat tyre, defective wheel, headset failure and pedal mounting failure can affect these bicycles. The use of taxonomy which is also considered as a semantic knowledge representation technique was used to establish the hierarchy of the created concepts. It was noticed that one of main advantages of SemanticGuide is that it can depict a systemic overview of the created concepts. However, it fails to illustrate a visual representation of the ontological model (relations between concepts). Furthermore, the semantic network itself mainly exists between the concepts. It does not exist between the rule definitions.

The definition of generic and specific knowledge areas suggests that problems can be resolved at lower levels of abstraction. Furthermore, attaching documents to symptoms of knowledge area enhances problem resolution and the definition of synonyms makes it easier for users to get along within the knowledge base. For example, noise was also defined as sound. Also, one could document experts' details (name, phone number, etc) in each knowledge area. This is effective if one is dealing with multiple experts and if the knowledge base being modelled is extremely complex.

4.2.2 Add Symptoms and Solutions

Once the knowledge area has been defined, the next step is to add symptoms and solutions for the defined knowledge area. A symptom is a characteristic or indication of a problem. A symptom has solutions which consist of causes and actions. It is essential to note that the solutions are recorded in order of frequency. This means the most common solution for a symptom occurrence within a knowledge area is recorded first within the knowledge base. The status quo of the knowledge base states that 40 symptoms have been included for the bicycle knowledge areas. An example of a resolution for a knowledge area is illustrated in Fig. 3. The reusability of symptoms and solutions is one of the core advantages of SemanticGuide. The use of a global solution and question pool allows for re-usability of diagnosis questions and answers which saves time and effort. Furthermore, it was identified that the global pool of knowledge can be defined first instead of concepts creation. This functionality reinforces user-friendliness.

4.2.3 Graphical Diagnosis Modelling

The graphical diagnosis editor allows for the graphical representation of the diagnostic process modelling which adds clarity to an explanation and makes functionality editing easier. The GDE allows for the declaration of If/else rule statements which represents the diagnostic logic for each symptom within a knowledge area. In this process, it was useful to construct a small answering outline that suggests how the answering options are selected to guide the user up to the problem solution. There is also reusability of the stored questions within the knowledge base. Furthermore, every recorded solution within the knowledge base is saved in a global solution pool; therefore, it is possible to record solutions and add them to symptoms later. The modelling approach has proven that Semantic technology allows for

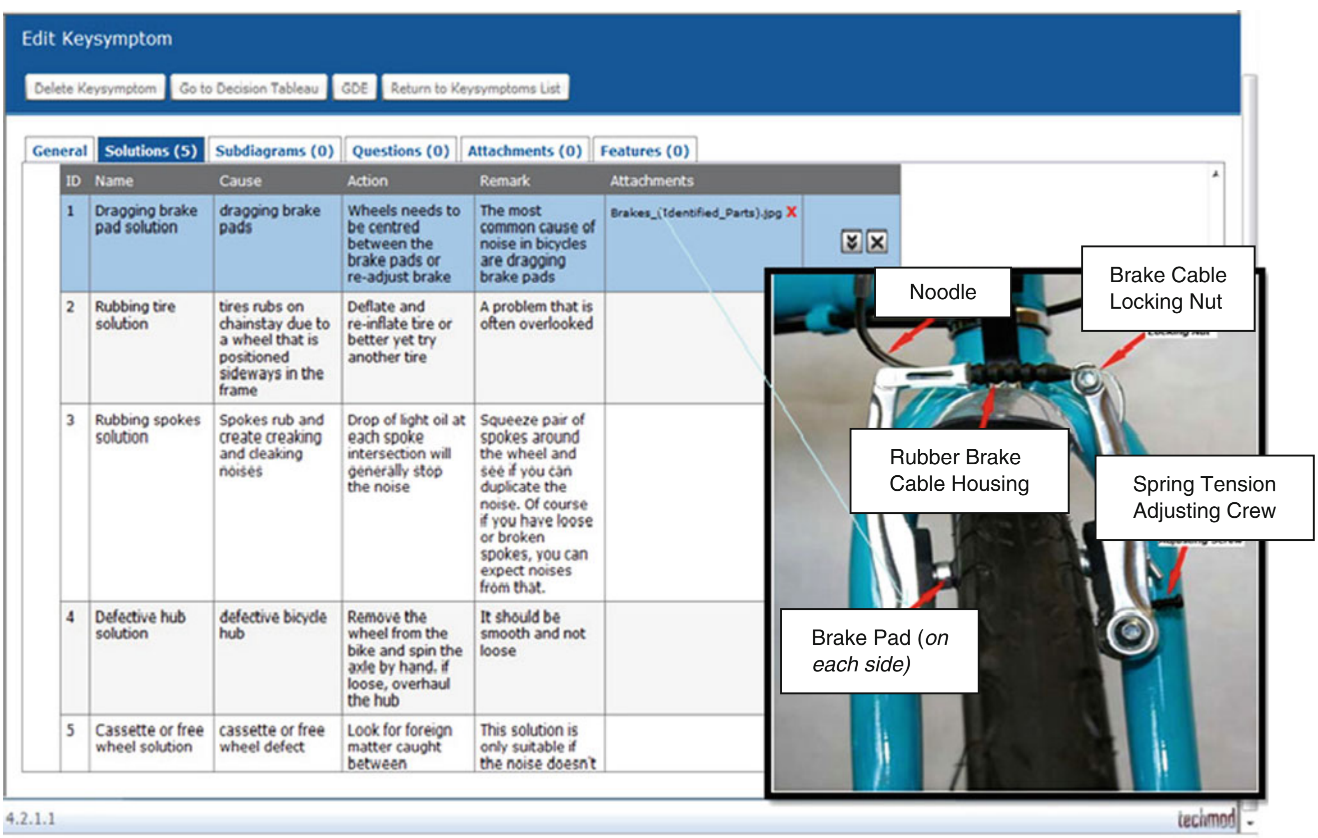

Fig. 3 Resolutions for knowledge area bicycle/nois

declarative rules which are rules that can adapt to change of data rather than the traditional procedural rules. This means that rules can be defined without data availability and once the data is available, the rule automatically fires which is not the case for traditional rules declaration.

4.2.4 Knowledge Base Export

Once the knowledge base has been developed and the diagnostic process has been modelled, the next step is then to release the knowledge base for SemanticGuide.

A simple 3 step process is used to deploy the knowledge base designer and release the problem resolution functionality to the rest of the world. The first step is to create the update files, followed by creating the new knowledge base and lastly copying the knowledge base into the update folder. Furthermore, the knowledge base export process suggests that SemanticGuide can be deployed gradually which means it can mature with the platform. The knowledge base export process also automatically creates and sorts ontologies within the knowledge base for SemanticGuide to utilise.

4.2.5 SemanticGuide Online Advisory System

Finally, once the knowledge base has been exported for SemanticGuide, the user can now interact and access the diagnosis process developed within the knowledge base. The modelled knowledge base is embedded within a user friendly interface offered by SemanticGuide. The diagnostic process logic guides the user to arrive at an appropriate solution and the user can select solution failure/success rates which act as input to the BIRT (business intelligence and reporting tools) analysis. This helps businesses identify which areas need focused improvement in order to maximise business performance.

5 Validation

During the development of the semantic based prototype, the validation of results and knowledge were also incorporated. One of the key strengths about the adopted methodology is that an expert was present during the development of the semantic based prototype. This helped in correcting and editing errors within SemanticGuide and ensured the verification and validation of knowledge within SemanticGuide for the bicycle maintenance support.

Furthermore, a standard bicycle manual repair document was used to model the problem domain. This explicit documented knowledge aided in validating the prototype. One can assume that the standards that created the model have already verified and validated the knowledge included within the standard. The bicycle manual was developed by a team of bicycle experts which reinforces the validation of this particular semantic based prototype.

This research project relied heavily on the "Barnett's" manual repair for bicycle maintenance and an expert. For this purpose, it is imperative to identify the difficulty of transforming this knowledge source into a semantic based platform. This is due to the complexity of capturing and understanding various knowledge forms.

Although, the bicycle manual was explicitly documented, it was challenging to acquire the knowledge needed to develop the diagnostic logic for each knowledge area. It was vital for the researcher to adopt a qualitative approach in observing and understanding the know-how of the expert's knowledge which enabled the accurate capture and implementation of the semantic based prototype for product maintenance support.

6 Conclusions

The development of a semantic based prototype to enhance the management and maintenance of knowledge has been demonstrated. There is a need to efficiently and effectively manage knowledge resources through the use of semantics and ontologies. In order to successfully construct this practical case study, the UML use case diagram was used to illustrate how the system (actors) interacts with the external environment. This helped in identifying the roles, functionalities and boundaries within SemanticGuide. Furthermore, the use of the taxonomy knowledge representation technique established the generalisation/specialisation hierarchical construction within SemanticGuide. As stated earlier, one of the main disadvantages of the application is that it fails to depict the ontological representation of the knowledge base and simply tabulates the concepts hierarchy within the domain. Furthermore, the semantic relations are only defined between the developed concepts. The semantic application fails to define the ontological relations between the rule definitions. However, one of the main benefits of using this semantic technology is that it offers reusability and maintainability.

The re-usability of concepts and rules are an imperative factor in use of semantic technology. This has been identified within SemanticGuide when adding symptoms and solutions to the knowledge base and during the modelling of the graphical rules.

The developed semantic based prototypes also proved that semantic technology is dynamic in nature. It adapts and changes over time. The functionalities within SemanticGuide can be deployed gradually which means that it can mature with the platform. This is achieved through the knowledge base export functionality as explained earlier. Semantic technology also allows for declarative rules which are rules that can adapt to change of data rather than the traditional procedural rules as explained in the graphical diagnosis rule modelling section.

Furthermore, it was noticed through critical analysis that the use of semantic application is very similar to that of object oriented programming. The main three of OOP are inheritance, encapsulation and polymorphism. Semantics has the capability to portray these three key features. However, semantic technology is different because of the use of synonyms which allows one or more words to be interchanged within a context. This gives semantic technology an advantage over the OOP paradigm. An example of this was illustrated earlier when noise was also defined as sound within a knowledge area of SemanticGuide. Finally, this research project has quantified the use and benefits of semantic technology to manage knowledge. This technology is highly scalable and can be used to model a more complex domain such as maintenance of an aircraft. Moreover, such a complex domain will contain thousands of declarative rules. However, Semantic technology has proven it can adapt to such complexity and can be applied to any industrial field due to its dynamic, adaptive and evolving nature.

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Early Stage Design in Global Product Development

Towards a Guideline for the Early Stage of Product Development

A. Hesmer, H. Duin, and K.-D. Thoben

Abstract Product development is highly focussed on the "value add to cost" within product generation by increasing efficiency in the physical product generation. Product testing or manufacturing activities are performed off-shore in dependency on the cost. This chapter states the importance of stretching the view within product development to the early stage in the development process where products are defined. Within this phases the corpus of product development costs are determined. In the sensitisation and support of involved employees and stakeholders for the operational work in the early development phases lies high potential for increasing the quality of the creational works' outcome. An approach as a guideline for the early stage of product development is described and ICT tools to support located and dislocated teams within their work are introduced.

Keywords Non-specific design phase · Early-stage-innovation · Collaborative innovation · Product development

1 Introduction

Products are global. Production is global, sales are global, usage is global. But is the determination of product requirements also global? Is the product developers' knowledge of global nature? Shouldn't developers understand the requirements and opportunities a market requests and offers to generate successful innovative products?

Publicly product development is associated with the design, technical development or testing of prototypes and new products. This is determined in the specific product development phase.

For companies product development starts much earlier with – in case of a product replacement – the analysis of data from the usage of the current model, the definition of requirements for the new product based on market knowledge and the specification of the new product e.g. in a product profile. These work steps take place in the non-specific or early stage of the product development process.

Up to 75% of all costs within the course of product development are determined in the phases from idea generation to product conception [1]. Taken into account the high costs in product development the understanding and the successful support of the early stages becomes indispensable for economical success. Studies within the engineering industry indicate that companies which reduce uncertainties in the early stages in the product generation are more successful in product innovation [2, 3].

Global Product development focusses on the "value add to cost" within product generation. As products are globally introduced nowadays companies should also focus on the phases in which the products are determined to answer the customers' demands worldwide and therefore create a better "value add to cost".

This chapter states an approach as a guideline for acting in the early stage in the innovation and product development process and introduces ICT tools to support individuals and teams within collaborative ideation. The approach presented here underlies the persuasion that collaborating teams with members of diverse disciplines will produce a higher quality within their results as their diverse knowledge is taken into account. As the approaches, methods and models applied within the engineering discipline focuses on technical activities the work presented here targets the preliminary and operational activities within the phases of knowledge generation, product finding and planning. The sensitisation for the importance of the preliminary activities to product development is mandatory to enhance the quality within knowledge generation, idea generation, evaluation and concept development.

The ICT tools presented address the requirements from the work in the non-specific design phase. They are conducted as web based services and therefore act as collaborative working environments for located as much as for dislocated individuals and teams.

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2 The Non-specific Design Phase

The product development process can roughly be devided in the specific and the non-specific design phase. As the specific design phase covers all steps to bring a product concept into life, the non-specific design phase deals with all steps to generate a product concept.

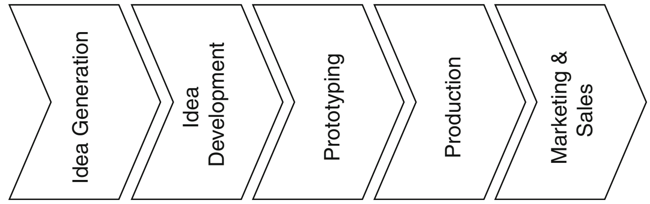

Fig. 2 Innovation process [7]

2.1 Product Development and Innovation

The product generation process addresses all effort taken to define and specify a product (product planning) to the physical product development.

The terms "product generation process" is synonymous to "product development process". Within this chapter the term "product development process (PDP)" shall be understood as both phases:

product planning
+ product development
= product development process

As the specific design phase covers the physical product development processes the non-specific design phase deals with the strategic and operative product planning.

The operative product planning is constituted of product finding and product planning [4] (Figs. 1 and 2).

Product finding is the creative and determining phase in product development processes. Commonly the work in this phase is reduced to the usage of creative techniques and the creation of ideas. The input to be taken into account is offered by marketing. The outcome of these phases is frequently considered to be innovative.

In public innovation is often seen as the invention of something groundbreaking new. It is associated with the work of the individual genius or a technical development department of one company. Schumpeter describes innovation as the invention or new combination of known objects [5]. But innovation is not solely concerned with the generation of new ideas but also with making an economical effort out of them. Innovation encompasses the entire process from the generation of an idea to the penetration of the market with an economically successful implementation of the idea – as much for products as for processes or services [6].

The early stages within the PDP and the innovation process refer to the same operational work.

2.2 The Importance of the Early Stages

The early stage or the "fuzzy front end" of product development is one main factor for the success of an innovation project. Cooper describes the early stage in innovation processes as the phases which separates the winners from the losers [8].

Referring to R. Bauer 85% of product development time is invested in products which never reach the market [9]. Furthermore only 18% of the innovations brought into the market prove sustainably successful. The figures show the high potential in increasing effectiveness and efficiency with innovation development.

The work performed can be summarized by the phrase "ideation". Ideation is basically a circular process that differs significantly from the sequential process approach that most people are trained in [10]. Furthermore, ideation is an inter-disciplinary and cross-organisational process that

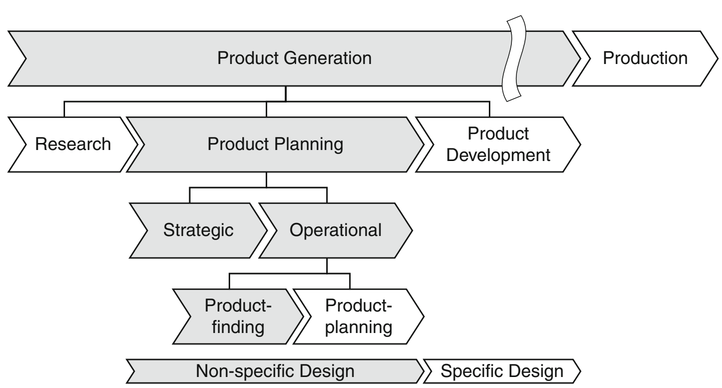

Fig. 1 The Product development process

requires a certain degree of common language. Additionally due to the inter-disciplinary nature the common language has to be neutral [11].

Ideation is a concept that is generally not understood well in depth. It is described to be the processes of discovering *what* to make*, for whom*, understand *why* to make it and define the success criteria including the development of insights for answering these strategic questions. Ideation as part of the overall innovation process is defined by Vaghefi as the "ability one has to conceive, or recognize through the act of insight, useful ideas" [12]. In many organisations ideation is viewed similar to creating ideas. However, creating ideas is only the very initial seed for the ideation process. Recent empirical studies have revealed that the process of generating ideas is not considered as a problem in industrial organisations – the perceived problem is the continuing idea development process – the ideation process [13].

As the products are defined in the idea generation and idea development phases the "fuzzy front end of innovation" moves in the focus of developers. Activities taking place in these phases are the idea generation, the evaluation of ideas and their concretion in form of product specification. The early stages are characterized by high uncertainties and the constant generation of new and relevant knowledge [7]. The knowledge is generated and immediately used in non linear work steps. Information from several stakeholders in a product development is needed to assure an innovation will meet the market or user requirements. To develop successful innovations companies use several methods to determine the customers' demands. The integration of end-users and other stakeholders into innovation projects has proved to reduce business risks such as the invention and acceptance of products, services and applications. However, the integration of the end-users remains a difficult task. Marketing and focus groups are relatively well known sources of information.

More and more innovation takes place in distributed teams where collaborative working environments support the communication between workers and provide shared access to contents and allowing distributed actors to seamlessly work together towards common goals.

These early phases of the innovation process are also represented in the product development process but subsummated under "Product Planning" or more specific "Product Finding".

3 An Appoach as a Guideline for Acting in the Non-Specific Design Phase

Traditionally, problems have been seen as complicated challenges that should be solved by breaking them down into smaller and smaller chunks. However, most modern problems – and ideation problems in particular – are complex rather than complicated. Complex problems are messier and more ambiguous in nature; they are more connected to other, often very different problems; more likely to react in unpredictable non-linear ways; and more likely to produce unintended consequences.

To successfully support the early stages of the non-specific design phase any approach to structure the work processes needs to focus on the real way of working and the intuitive processes of innovators [14].

The approach presented is based on a state-of-the-art analysis in the field of innovation management, design theory and product development. Additional primary research by observing innovators, innovation teams and designers lead to incremental insights of the daily work to be performed within working in ideation projects.

Because of its fuzzy nature, where details and even goals are not defined exactly the early stage in the DPD can not take place in a linear process. Iterations are the nature of the related workflows. Results of the observation and interviews clearly show that creating and developing ideas is based on iterative routines of representing an idea, sharing it with others, getting feedback and communicating about the object (the representation). They conduct the routines as long as the maturity of the information achieved or generated provides value to the product development. Within the approach presented the focus of ideation processes is moved from the creative part (e.g. idea generation via brainstorming) to the generation of knowledge before defining any specification. Furthermore the process integrates relevant stakeholders to assure a common learning process of an organisation and therefore reduce the risk of un-acceptance of innovation within the organisation. The process supports preliminary activities to the DPD and the creation and development of knowledge and ideas, viewing ideation as a working process rather than moments of divine inspiration. It will identify explicit activities and routines for team-based ideation work.

3.1 The Overall Structure of the Approach Guiding Through the Early Stages of the DPD

The overall process is divided into three phases separated by dashed lines in Fig. 3: *Project Initiation, Knowledge Exploration* and *Ideation*.

The work is performed by persons on two levels: the operational (innovators) and the management level. Both interact with each other. The field for operational work of the innovators is the field of exploration – the information basis for the innovators: the *levels of action* (represented by arrows).

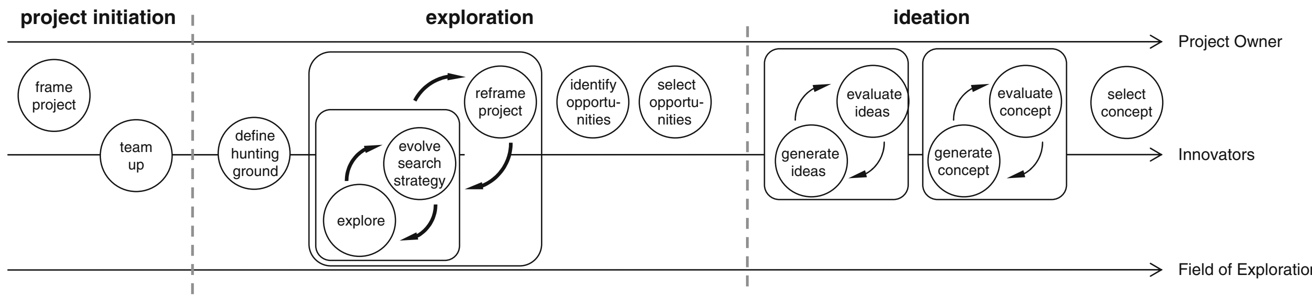

Fig. 3 The overall structure

A single work step is defined as activity. *Activities* (represented by circles) are performed by an individual or a team to create, enhance or evaluate the information basis for the product development.

Routines (represented by boxes) describe the interrelation between activities. They consist of two or more activities but also generate a value on their own. These routines are of an iterative nature. Innovators or other persons involved in the process run through them several times before generating a defined result. These routines defined describe the innovation workers operating in the field of exploring knowledge and within idea and concept generation. Teams work systematically with managing iterations and change in open-ended projects, with quick feedback loops, and with facilitating disciplined innovation meetings, all of which accelerating the emergence of surprising strategic insights.

3.2 The Three Levels of Action of the Approach

The levels of action describe on the one hand the stakeholders or active persons in the operational work in the early-stages of the PDP and on the other hand the area of action – the field of exploration.

The *field of exploration* is the target for research and the source of learning. It comprises secondary research, field and user research or primary research. This means existing and potential users and other external stakeholders. It means technologies, literature, databases, cultural artefacts and other man-made objects to learn from. It also means experts. And it means biological and physical matter to investigate and experiment with.

The field of exploration gives resistance and direction to new insights and interpretations made by the team of innovators, thus ensuring that their results are relevant to the world. It is a source for problems to work on, needs and values to take into account, and solutions that could be possible.

The *innovators* are the team or the individual that does the majority of the work. They are learning from the field of exploration, they are creating insights, and building hypotheses. They are identifying opportunities, generating new ideas, and making robust concepts. The team can be small, only consisting of a few persons, or large with several subgroups. A large group will, however, still have a small core that manages and governs the project – both in terms of resource allocation and to drive integration of insights and ideas.

The *project manager* is the guide and mediator for the team of innovators. He is the link to the overall organisation or overall strategic interest, the supplier of resources and the operational decision maker. Depending on the teams and project size there might be a project management team.

3.3 The Three Phases of the Approach

3.3.1 Project Initiation

Project Initiation is the phase before the operational works starts. Project initiation can be performed e.g. in a kick-off meeting for the development project. The Project Initiation Phase sets up the structures using two different strategies: an outside-in, and inside-out. Outside-in is done together with the Project Manager, where the project is framed. Inside-out is about teaming up and setting up the work structures and internal expectations that ensure productivity and creativity.

Frame Project is an activity that results in the brief and scope that will guide the innovators through their exploration and ideation. Success criteria should be defined in this phase and a clarification about the representation of the outcome should be achieved.

Questions to be answered within the project initiation can be:

- What do you know or think you know about this?
- What don't you know about this that you'd like to know?
- Why is this goal important to you?
- What is stopping you from achieving your goal?

- How do your competitors perceive your situation?
- What might you be assuming that you don't have to assume? What don't we understand?

Within the early stages in product development the innovators – may it be engineers, product designers, sales person etc. – doing the operational work. This multi-disciplinary team is lead by a project manager who links the team to the organisational interests. *Team Up* is about bringing a team together with a diversity of disciplines, competencies, perspectives and mind sets. This will stimulate learning and creativity. Within the Activity Team Up the team prepares for the open ended task, creating work structures that accelerate learning and keep frustration in check (Figs. 4 and 5).

3.3.2 Knowledge Exploration

Key to new ideas and concepts is the knowledge and information about the products' environment, the users and their usage of products, competitors and developments. This can be intrinsic knowledge of the developers but also a wider view on the product to be developed and therefore research in related fields – the knowledge exploration – is necessary.

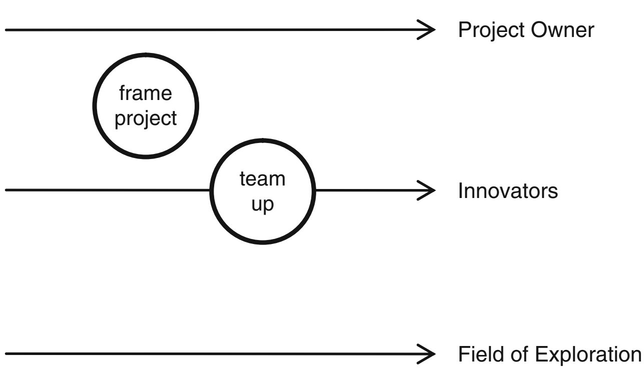

Fig. 4 Project initiation

This means that traditional approaches to action planning and project management can be problematic to apply. Early commitments of resources (money, time, attention, and expectations) make it difficult to react to and build on new insights gained.

The resulting insights from knowledge exploration will thus emerge from the research of the team rather than being planned in advance. Each task produces a stepping stone which helps the team venture further into the unknown. By focusing on iterations of small research tasks surprising insights are more likely to emerge than by working in larger chunks.

New knowledge and understanding is the backbone in the innovation process. This phase is the key in producing new knowledge and in transforming the shared understandings for usage in the product development. The phase ends ostensibly when a number of opportunities have been identified, settled and selected.

First step is the *definition of the hunting ground* – it's the answer to "What do we need and want to know?" This is about identifying interesting themes and questions that the innovators can use as outset of their exploration. Within the *Exploration* the information basis is screened, valuable information is collected and documented. The findings are evaluated. This leads to an *evolved search strategy* and this happens in fasts iterations in the *search routine* between research and reflection. In each iteration the team answers new questions and produces memos that can serve as building blocks towards larger understanding. This process forces the innovators to reflect on their work continuously in order to stay sensitive to new learnings and in order to make sure that their continued work is responsive to their learnings. Within the process of working the knowledge generated might lead to the accommodation of the development project. This is represented in the *reframe routine*. The search and reframe routines lead to the *identification* of new *opportunities* for product development which need to be *selected* as starting point for idea and concept generation.

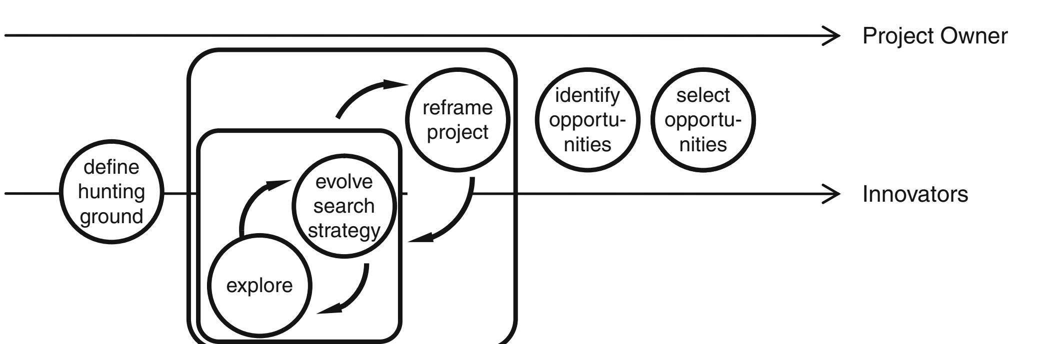

Fig. 5 Knowledge exploration

3.3.3 Ideation

Based on the knowledge exploration ideas and concept are generated. Idea generation is often seen as the inspiration or intuition of an individual. *Ideation* can also be seen as outcome of a work process. The operational work taking place within the idea generation can be described as the conversion of knowledge achieved in the exploration phase to new ideas or a new combination of known objects. The generation activity covers the generation of first ideas and their revision and enhancement. Idea generation connotes the directed generation of new ideas to solve a problem. Methods and tools are used to define the problems more precisely, to accelerate the idea generation of individuals and groups or to break down mind logjams. The generation phase is mandatory.

The building blocks of the idea generation activity are the following:

- Recall knowledge from exploration phase
- Generate ideas e.g. by brainstorming, brainwriting or – more advanced – TRIZ methodology
- Represent ideas: The form of representation is conditioned by the maturity of the idea and the idea development process. The idea can be represented e.g. by verbal description (not recommended), a buzzword, a written description, a sketch or a combination of these.

To increase the maturity of selected ideas a continuous challenge of the current status of the idea and evolving the idea is needed. This is done by a steady evaluation of the outcome of the activity generate ideas. This *idea evaluation* is of informal nature as it needs to be done often and quick within the iterative routine of generating and evaluating ideas – alias *idea generation routine*. Common methods to use are for example the "one-point-choice" or "multi-point-choice" method.

The evaluated and chosen ideas need to be enhanced to product concepts within the activity *generate concept*. A concept is based on an idea but one of mature nature. It needs to represent (e.g. in a product profile) the interests and prospects an organisation has to develop the product and bring it to the market. It includes requirements from related disciplines like marketing, sales or production. The information and knowledge from these disciplines act as much as input to the concept and as the evaluation criteria. Therefore, *concept evaluation* is taking place on operational level as new information and knowledge is fed back to concepts that evolve during the *concept development routine*.

The *selection of concept* closes the phase of the early stages in the PDP (Fig. 6).

4 Requirements for Tool Support

Collaborative work environments supporting these phases of the early stage of the PDP (in the following called CWE4PDPs) show a number of requirements to be fulfilled to guarantee effective and efficient working. The most important need is almost self-evident: The environment needs to allow access anytime from anywhere in the world. It must be as open as possible but at the same time securing and structuring the access to information and processing tools of the end-users. In particular, the following requirements can be defined:

A CWE4PDP must support the execution of loosely structured processes as described before but at the same time offering *guidance* to the end-users. Guidance in this sense means the provision of clear information about information (concerning the product to be developed as well as meta-information such as current status and involved personnel) and available methods and tools. Information needs to be presented according to the different roles of the end-users (project manager, innovator, etc.).

Very much connected with guidance is the *adaptability* of the CWE4PDP system. The leading idea is that the system can conclude from the status of the project and the profiles of the users what and how to present in the user interface. This includes easy access to the underlying methods and tools depending on the user profiles.

Any CWE4PDP system must support *synchronous and asynchronous collaborative working* for all persons involved.

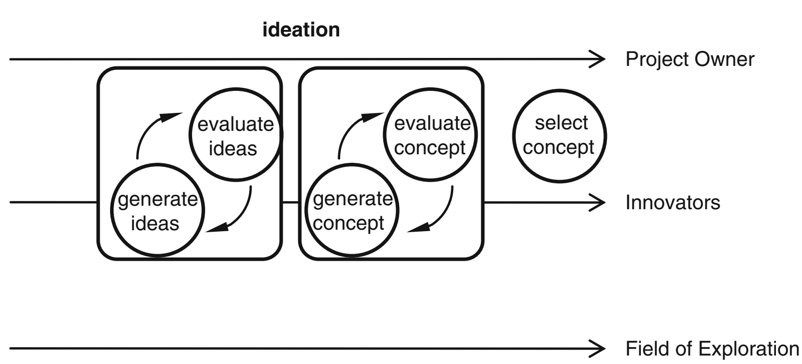

Fig. 6 Idea and concept generation

The system should not restrict the usage of information and tools and thus hampering the creativity of the innovators.

Last but least, a CWE4PDP system needs to provide some kind of *agile project management methods* allowing instantaneous planning and the monitoring of progress respectively the current status of the project.

Beside these general requirements the single phases have their own specific needs.

4.1 Project Initiation

One of the main tasks in the project initiation phase is the team building which means the assembly of an interdisciplinary team to work on the PDP project. Therefore, there must be capabilities to find the 'right' experts based on various qualities such as competences, knowledge, experiences, availability and socialisation of experts.

4.2 Knowledge Exploration

Once the team has been set-up collaborative tasks are mainly dealing with exploration of the hunting ground which may results in a reframing of the project. Therefore, there must be capabilities to commonly build-up and maintain a knowledge base which includes the integration of already available (external) knowledge bases.

4.3 Idea and Concept Generation

The phase of ideation and concept generation has several requirements which need to be supported.

Firstly, the integration of creativity methods such as brainstorming, distributed brainstorming or Synectics needs to be carried out and the involved innovators' disposal.

Secondly, there must be a mechanism allowing the management of generated ideas and concepts. New knowledge may require further work on ideas in order to change or refine them. This requirement is much connected with a common repository as described below.

The third requirement concerns the evaluation and/or ranking of ideas within the group of innovators and a wider community.

4.4 Idea Repository

A central repository storing all ideas and concepts related to the innovation project needs to fulfil several requirements.

Ideas and concepts need to be described by general attributes like name, description and creation date. Beside this, there should be a tagging and commenting system and ideas and concepts should be related to projects, persons and to each other. Also optional evaluations and ratings need to be stored together with the ideas and concepts.

5 ICT Tools

The European Integrating Project Laboranova developed a set of Web-based tools to support the areas of team building, ideation and evaluation in collaborative innovation processes [15]. Tools are integrated via an idea repository and are accessed in a mash-up user interface. Specific tools are presented here, exhaustive information is found on www.laboranova.com.

5.1 Project Initiation Support

The *Profile System* is designed to allow system members to record their interests and expertise. It shows the importance of recording people's interests and expertise both from them and from their interaction with the system. This allows rich profiling of individuals involved in innovation processes.

The *People Concepts Networking* (PCN) tool is built into the profile system. The tool builds an index of the concepts existing in the profile system from those entered by the users or entered by the system. These concepts can then be used to find other people using those same concepts in their work.

5.2 Collaborative Web Search

The *Social and Collaborative Web Search* (SCWS) turns dispersed relevant sources (web sites, blogs, wiki, documents, videos, etc.) into one resource shared for defined groups of users. This approach uses the collaborative intelligence in order to organize, share and access distributed knowledge.

5.3 Distributed Brain Storming

The distributed brainstorming tool *Melodie* shows all ideas as a cartography which visualises all results. There is a semantic system which links all same topics between them to better assimilate results. Moreover, people can improve ideas by entering ideas of innovation.

5.4 Ideation Games

Two different ideation games have been developed following the concept of disrupting traditional idea generation methods like brainstorming by a radical change of perspective.

refQuest is a disruptive innovation game based on the concept of ‘reframing the question’. The players enter a process where they select different perspectives and apply a creativity technique like Synectics [16]. A moderator is observing the course of the game and may intervenes by letting unexpected events occur (disruption). This should stimulate the creativity of the players. The result of the game is a list of rated ideas which can be used to be worked on further.

The second game is called *TheTakeover*. The objective of this game is to change the perspective by introducing to the participants the fact that another enterprise has taken over the own company and current products and services need to fit within that new portfolio [17].

5.5 Idea Evaluation

The *Idea Evaluation Market* (IDEM) is based on the idea of prediction markets. People can put their ideas on internal prediction markets (PMs) and thereby explore and participate in a collaborative evaluation process [18].

The participants can bet on the future success of ideas using virtual stocks representing future events whose price is a function of transactions representing individual probability-estimates of the event happening.

The result is a prediction market that aggregates knowledge from many individuals in order to involve a broad base of insight in the evaluation of new ideas and concepts.

5.6 Monitoring

The *Innovation Scoreboard* is a tool that provides qualitative and quantitative information pertaining to the innovation process and the activity within the Laboranova platform.

Features include a set of key performance indicators on the global and user levels, a message area allowing managers and executives to broadcast strategic directions and innovation objectives, a powerful dashboard and reporting tool for innovation managers and an on-line innovation survey to evaluate the innovation process.

The Innovation Scoreboard is thus a transversal module that aggregates data and presents them into a customisable, user-friendly interface.

5.7 Idea Repository

The Idea Repository is the central part of the tool set. It implements a complex database storing ideas and concepts allowing the correlation of much information such as tags, users and any kind of supporting data.

From an architectural view, the Idea Repository provides the central integration instance enabling all tools to share common data. Its services are provided using the REST (Representaional State Transfer) technology.

6 Summary

The approach presented in this chapter is a guideline for innovators within their work in the early stages of the product development process. Process participants should represent the stake holding disciplines in a product. This includes stakeholders inside a company from all relevant markets as well as the customers from different the markets the product should be introduced to. The intrinsic knowledge of customers is very valuable in the process of product definition. The approach defines phases to give a guideline to innovators and companies and wants to raise the attention to ideation processes and create awareness for the importance for product development.

The global product development within the early-phases is hooked on the usage of an information and communication infrastructure. The effectiveness and efficiency of the work can be increased by the usage of specific IT tools, such as idea management tools, collaborative brainstorming or evaluation tools. These platforms need to assure a support of the representations used within the early phases of product development.

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A New Approach for the Development of a Creative Method to Stimulate Responsible Innovation

B. Tyl, J. Legardeur, D. Millet, A. Falchi, and B. Ranvier

Abstract Sustainable development forces companies towards eco-design. It often appears to be a constraint which does not encourage a calling into question of the product or service. It is also necessary to surpass this procedure by integrating the notion of creativity while keeping the coherence of the social and environmental aspects through an eco-innovation initiative. This chapter first presents the "eco-innovation" concept and a review of some eco-innovation tools, in order to identify their characteristics, and then, the paper describes a newly developed tool, "ecoASIT", which is an eco-innovation tool based on a "closed world" notion and which implies that responsible innovation does not have to introduce new elements in the world of the problem.

Keywords EcoASIT · Responsible innovation · Sustainable innovation · Eco-design

1 Introduction

Today, our planet is confronted to a degradation of its natural environment. By our activities and the production of impacting products, we are now in front of an environmental and social emergency which requires a total rethinking not only of our production system, but also of our way of consuming and designing. In order to satisfy our needs, our challenge is to develop new sustainable alternatives [1].

Therefore, if in the 1980s, the stress was successively on a quality approach and on innovation to face worldwide competition, today, working on new approaches (methods, tools, organizations...) has become essential to reach responsible innovation and still permit the development of products and services which have a meaning for the society.

In this chapter, a first part will define eco-innovation and sets this concept back in context. Then, a second part will focus on a review of some existing eco-innovation tools, in order to present the research hypothesis and an analysis of the important characteristics that an eco-innovation tool must meet.

To finish, a first prototype of the tool called ecoASIT will be suggested. It is the result of a first research based on the adaptation of the ASIT method to eco-innovation needs.

2 From Eco-design to Eco-innovation

2.1 Limits of Eco-design

To fulfill these new sustainable development challenges, companies have to make their design process evolve in order to integrate the environmental dimension of sustainable development in the design of the product.

This process, called eco-design, is defined according to the international ISO 14 062 norm, like the integration of environmental constraints in the development process of product design [2].

This approach relies on two main principles: a global approach and a multicriteria approach. The global approach allows the consideration of the product or the service in the whole life cycle (raw materials, production, manufacture, distribution, use and end of life), whereas the multicriteria approach considers the complexity of environment through different environmental impacts.

Actually, eco-design corresponds to different approaches such as the Life Cycle Assessment (LCA), Design For Environment (DFE) (Design for assembly/disassembly,

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design for recycling) which generally leads to proposals and improvement recommendations, to redesign the product.

Indeed, Sherwin underlines that today, current practice in eco-design focuses on the study of the technological part of the system, only suggesting recommendations [3].

But, as eco-design is based on through preliminary studies (such as LCA) which lead to think per component and not per function [4], it cannot always end to a calling into question of the product but it can only give corrective solutions in a well defined perimeter.

Moreover, these analyses generally imply a high detail level of the product which sometimes defeats the purpose of creativity's needs. In order to give the best perspectives and to have the largest view on the product or service to design, it is generally allowed to intervene upstream during design and innovation projects. But nowadays, many authors note that very few tools have been developed and used during these stages of the development process [5].

Figure 1 shows the environmental improvements of the products according to their innovation level. Nuij clearly indicates that eco-innovation aims at developing products which do not come from redesign or incremental innovation, but concern levels 3 and 4 [6]. We can note that it is interesting to move to a higher innovation level (levels 3 and 4) but these levels imply to surpass a "simple" design approach to reach a more social one [7].

So, according to current challenges, eco-design, in its restrictive meaning, can show its limits. It is important to carry out a new approach to move from a redesign approach to one which leads to a calling into question of the product [5] in order to change from a reactive design to a proactive idea generating design [9].

2.2 Towards Eco-innovation

It has become necessary to help the actors of the companies to rethink the products and services in order to propose real design eco-innovating alternatives. To do so, it is most important to combine and hybridize eco-design, innovation and creativity to an approach named: eco-innovation.

Eco-innovation is not yet a usual practice in companies [10]. It is a synergy between eco-design and innovating design, and is surely not only a creative session following an eco-design study. This approach also has to surpass the stage of the "simple" impact reduction, to move forward and search for a real added value coming from a more global consideration.

However, in opposition to eco-design which is relatively well-defined, the eco-innovation expression is used to name every innovation which seems to reduce the environmental impacts like a catalytic converter or a particle filter.

Therefore, it is necessary to try to define the process and the results to obtain properly.

In some studies, we can observe, by compiling in the literature different definitions that include the environmental innovation activity, that the eco-innovation expression still remains very vast, with no proper definition [11]: some define it in a general way, or with the process, like James: "Eco-innovation is the process of developing new products, processes or services which provide customer and business value but significantly decreases environmental impact" [12]. Other underlines the necessary changeover intensity, as Baroulaki asserts: "Eco-Innovation is the implementation of radical ideas for environmentally friendly products and processes that will meet future needs" [13].

Nevertheless, everyone agrees to say that eco-innovation is mostly linked to environmental impact, whereas social and ethical aspects are often excluded [10, 11]. It is also relevant to note that eco-innovation is included in a more global concept of "sustainable design".

Sustainable design can be defined as a more global concept because it integrates the social and ethical side of sustainable development. This concept can also include aesthetical or emotional considerations [10, 14].

Consequently, innovation in sustainable development refers to different concepts that extend more or less the perimeter of action.

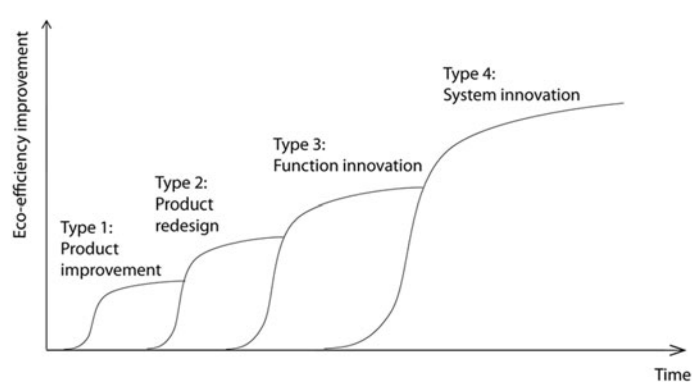


Fig. 1 Level of innovation [8]

Throughout all these reflections and definitions, this chapter proposes a definition of Responsible Innovation.

This concept can be described as an innovating reflection process on environmental, social and ethical responsibility, leading to the production of an innovating system.

This means that if we propose a wider reflection space without ignoring any of the sustainable development pillars, then the results will be even more relevant. It is then interesting to propose an analysis on three scales (individual, society, global) which represent as many front doors to innovation.

2.3 Eco-innovation Positive Approach

We can acknowledge that it still takes a lot of time for eco-design to take place in the industrial world [8] and that it still appears as a constraint. Taking into account the environment is felt today as a simple impact reduction. In order to make this integration easier for companies, it is crucial to introduce new methods which will lead to a positive approach of environmental products design and will help to surpass this negative impact reduction vision to a truly positive approach for the creation of new concepts [15].

To conclude, according to Baroulaki, eco-innovation has to target a radical innovation that – to resume Robertson's studies that classify innovations according to their impacts on behavior – has to provoke a profound change in the user's behavior [16].

This vision is positive because it integrates new simple, ethical values in its innovation process to tend toward a result that will be accepted by the user and will modify his vision.

If the intentions and the vision that responsible innovation proposes seem relatively promising, it is relevant to take an interest in the means which can orchestrate such an approach. This is the topic of the following parts of the article.

3 Review of Some Eco-innovation Tools

A lot of eco-innovation tools have been set up to facilitate the generation of sustainable products.

3.1 Eco Compass

Eco compass is an eco-innovation tool that has been widely studied and that suggests an evaluation and a reflection on the product around 6 axes: mass intensity, energy intensity, extending service and function, health and environmental risk, resource conservation, reuse and revalorization of waste [12]. It is a comparative spider diagram.

From this evaluation, a method is suggested using 7 stages, covering the whole innovation process. These 7 stages match to a setting up of the problem, then to an identification of opportunities, thanks to creative sessions, then to idea organization, and to finish results evaluation.

It is consequently a complete methodology but nevertheless, it seems to present some gaps in the idea generation stage and in the reflection orientation, because it does not suggest any methodological framework.

3.2 TRIZ in Eco-innovation

TRIZ is a theory, which consists of many sophisticated innovation tools, developed by Atshuller since 1946, aiming at overcoming psychological inertia to allow emergence of solution concept [17]. Atshuller centered his analysis on existing solution: the knowledge and tools are essentially extracted from the analysis of numerous patents. These analyses allowed the observation that an invention in one field is often a transposition of an existing solution in another field.

Based on this theory, several interesting tools has been developed, among which:

- the contradiction matrix, which generates general principles from parameters contradictions;
- the law of evolutions, allowing to model the evolution of technical systems;
- the ideal system, theoretical concept that states that system has to evolve towards ideality, where a system does not exist, while its function is performed;
- the separation principle (separating the parameter in space, time, or between the whole of an object/system and its parts).

The TRIZ methodology has been studied by many authors to be evaluated in eco-innovation.

Jones investigates the pertinence of contradiction matrix with eco compass principle. She underlines that some of these principles were not covered by the parameters of the matrix [5].

Chen highlighted eco-innovative examples for all the TRIZ principles [18] and tried to develop a TRIZ eco-innovative approach without the contradiction matrix, looking for relations between WBCSD principles [19] and matrix parameters [20].

Moreover, some authors tried to study the law of evolution to elaborate an eco-design guideline [21].

To finish, some applied TRIZ in DFx approach, like for example in design for disassembly [22].

But all these approaches on TRIZ seem to be heavy and above all ask a lot of time and a good expertise of the method. The TRIZ methodology is efficient, but only under specific conditions, on a well defined perimeter, and on technical problems, which do not fulfill eco-innovation preoccupations. Nevertheless, Jones tested a simplification approach, studying simplified TRIZ tools, as the separation principal and the ideality [5].

Finally, we can note that Russo suggests performing TRIZ with LCA during the evaluation phase and the setting up of the problems [21].

3.3 PIT

The Product Idea Tree is a tool which facilitates the eco-innovative idea generation, structuring the information and stimulating creativity [5]. This tool combines a design process model with starting points from environmental tools as eco compass, and mind mapping technique (Fig. 2).

The advantage is to allow exploring all the reflection aspects, combining radial reflection (design process) and key points (eco compass axis). It points out the expected type of result: strategic, conceptual, detailed, but showns that a structured method improves constructive communication between participants.

This method is a good way to favor idea generation and communication between participants, and also to structure the idea in cluster and to underline relevant ideas.

Nevertheless, this method is limited concerning the problem identification and appears constraining due to the complexity of combining radial and key point reflections.

Moreover, the idea generation (through key points) needs to be oriented in such a way to have a more global approach of sustainability.

3.4 MEPSS

One of the possible orientations for eco-innovation is the setting up of the Product Service System (PSS), which is a system combining services and physical products [23]. A methodology has been initiated by PriceWaterhouseCoopers

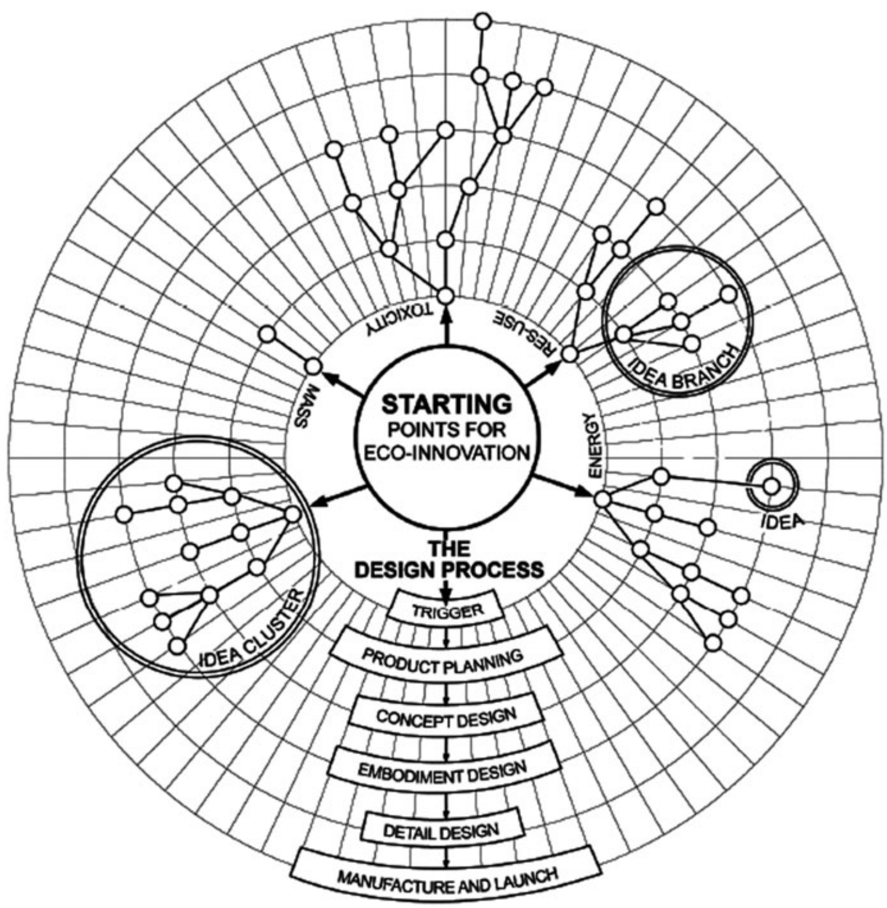


Fig. 2 PIT diagram [5]

to encourage the generation of innovating offer for PSS, thanks to a toolkit to go with an innovation process and orientate a design process towards sustainable solutions PSS. This method combines solution research (from guideline), idea generation and evaluation. It consists of 4 phases: strategic analysis, new research axis, PSS idea development and PSS development. This methodology has been developed in order to study the system from a global point of view.

It is a flexible and modular tool, a link between evaluation and design. Moreover, the tools are designed to work on three axes: environment (lifetime, resource conservation, toxicity), social (work condition, social cohesion. . .), and economic (long-term risk, added value for customer. . .)

This tool allows to identify interesting characteristics for an eco-innovation tool as flexibility, the global approach of the problematic, the stakeholders. . .

3.5 Information/Inspiration

The tool information/inspiration has been developed by the Loughborough University [24]. It is structured in two parts:

- “Information”, that presents different concrete data in eco-design.
- “Inspiration”, that presents eco-designed product.

These parts are closely linked in order to allow the user navigating between these two parts. These tools give liberty to the user, without chronologic framework and favoring the user appropriation.

4 Characteristics of Eco-innovation Tool

4.1 Research Problem

There are numerous tools for innovating design research or for eco-design. These tools lead to question on the criteria that a good eco-innovation tool must meet. Moreover, this eco-innovation tool has to be adapted to Small and Medium Enterprises (SME), which are the target of our research. These reflections have to solve two major problems:

How can we apprehend the creativity and innovation problem in sustainable development?

How can we understand a complex and systemic topic with a simple approach dedicated to SME?

A hypothesis unit has been established through fundamental questions to qualify the relevance of an eco-innovation tool. Therefore, 5 points are proposed which constitute the acceptation criteria of a powerful and logical eco-innovation tool.

4.2 Flexibility

The flexibility of a tool can be defined by the way it is integrated in the design process and the adaptation and interpretation skills of the user. Flexibility is a criterion for carrying out an eco-innovation tool [5]. It is relevant to wonder how a good appropriation of the tool can be successfully integrated in the company.

4.3 Complexity Level

The complexity of the tool is a strong axis of the reflection proposed. Indeed, a tool will be easily handled if it is simple to use, pleasant with an appropriated language [25]. It is fundamental to remain simple without multiplying the modules and the information necessary.

However, as it was previously said, the environment theme is systematic. Consequently, how can we conciliate systematic environment approach with the simplicity of the tool? Until which point can the tool stay accessible for SME?

As an example, numerous tools, in eco-design or in creativity, have lead to a simplifying road, such as ATEP tool [26], which has permitted the simplification of the LCA approach or in the case of problem resolution, the ASIT method [27], issued from the simplification of the TRIZ method [17].

4.4 Systematic Approach

Through the notion of complexity of the tool, we can also call for a new questioning about the perimeter of the reflection allowed by the tool. Indeed, it has been submitted that it is relevant to obtain a larger reflection space to obtain relevant ideas.

Consequently, a central aim of an eco-innovation tool is to know how to consider interaction between the different challenges of the sustainable development (environmental, social, ethic) in an eco-innovation tool?

Moreover, can a tool oriented for SME consider the systemic approach of sustainable development, without being complex to use?

4.5 Learning Potential

Literature clearly highlights that a creativity tool must interact with and between users, in order to stimulate information exchange and finally to learn to reason and to consider problem complexity [28]. So the reflection is to understand how a tool can facilitate awareness and learning of the responsible innovation approach, and how to apprehend the sustainable challenges in an autonomous way.

4.6 Setting Up of Problems and Idea Evaluation

A most concrete reflection is suggested and concerns different phases of the innovation process.

Indeed, the setting up of the problem in the early phase of innovation process is crucial for a creativity tool and more widely for an innovating design tool. The problem identification must be enough to not expend important creative effort "in vain to solve bad identified problem" [29]. So how can an innovation tool help in the identification of the most relevant problem, in a complex topic?

In the same way, it seems relevant to linger on the idea evaluation phase. It can be interesting to wonder if eco-innovation requires a particular evaluation, and how to help in this evaluation.

5 Carrying Out the First Eco-Innovation Tool Prototype Throughout a Cellular Phone Example

To answer the problem, ASIT tool has been identified as a starting point. It is a simplified version of the TRIZ tool. To quote Steve Tuner, ASIT appears to be extremely relevant for an eco-innovation tool because it permits the resolution of problems from the inside, with no introduction of additional resources [30].

5.1 ASIT

The ASIT method (Advanced Systematic Inventive Thinking) has been imagined by Roni Horowitz in order to simplify the use of the TRIZ method elaborated on works established in the beginning of the 1990s and more precisely of the "SIT" ("Systematic Inventive Thinking") by Genedy Filkovsky. He noted that the "world of solution" does not introduce new kind of objects compared to the "world of problem": the creative solutions are very close in their genealogy to conventional solutions. This constitutes the first condition to the ASIT method, known as "closed world" condition and corresponding to the TRIZ ideal notion. The "qualitative change" second condition can be explained with the use or the cancellation of the problem's cause. This condition permits to "break" the contradictions that we try to solve in TRIZ. These two conditions constitute the basis of the ASIT method and are accompanied by 5 tools (unification, division, multiplication, deletion, symmetry breaking) to identify the opportunities hidden inside the closed world [27].

The ASIT method (as for the TRIZ one) challenges the "quantity leads to quality" myth according to which "the more ideas we have to consider, the more we can discover new things" [31]. It does not rely on lateral thinking or out of subject reflection. To avoid these "fixations", psychological inertia, ASIT proposes a new "subject instead of thinking out of the border" [27]. Therefore, one of the strong points of ASIT and TRIZ methods is to fix directives. Concerning the quality of the solutions found: in TRIZ, this border is delimited by the problem's particular modeling; in ASIT, the closed world condition according to which "a new kind of object should not be added" emphasizes the idea of world of solution using the same components as the world of problem.

As the creative solutions are very close to the conventional solutions of their "genealogy", it is necessary to stay close of the center of the spiral representing the existing solutions. The ASIT method only proposes 2 conditions and 5 tools to promote creativity. The simple sentences generated can be used during collective sessions such as brainstorming to induce ideas.

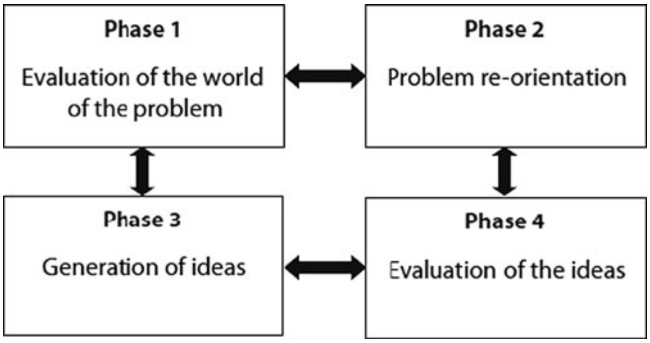
Thus the conditions are:

- The closed world condition aiming at looking for solutions which do not introduce new objects from the world of problem.
- The qualitative change condition, searching for solutions in which the effect of the main factor of the problem is either inverted or eliminated.

The 5 tools are:

- Unification tool: solve a problem by giving a new use to the existing object from the world of problem.
- Multiplication tool: solve a problem by introducing a slightly modified copy of an existing object in the current system.
- Division tool: solve a problem by dividing an object and re-organizing its parts.
- Symmetry break tool: solve a problem changing from a symmetric situation into an asymmetric one.
- Object removal tool: solve a problem by taking out an object of the system and assigning its function to an object remaining in the system.

Table 1 Presentation of ecoASIT process



Therefore, the ASIT method helps solving a great number of problems and is less time-consuming because its use is very simple compared to TRIZ.

This is why the hypothesis that the adaptation of the ASIT method can be efficient is relevant in an industrial context and especially when there is a spot creativity needed to find solutions focused on sustainable development. This is the subject of the following part.

5.2 *Transformation in ecoASIT*

The last part saw that eco-innovation requires new characteristics which must appear in the tool.

To meet these criteria, a first version of ecoASIT was suggested [32]. This version aimed at using ASIT method on eco-design issues.

This first version was completed by structuring it on four main phases which correspond to the different steps for our eco-innovation process (Table 1).

The first phase (steps 1 and 2) corresponds to the preliminary problem evaluation. The second phase (steps 3, 4 and 5) is the incubation, that is to say the reorientation of the problem. These two first phases form the basis required to make sure that we work on the relevant problem. The third phase (step 6) corresponds to ideas generation, and finally, the last phase (step 7) is the idea evaluation; but this will not be dealt in this chapter.

5.3 *Phase 1: Evaluation of the World of Problem*

The evaluation of the world of problem essentially consists in defining the problem's boundaries, and so setting up a first perimeter in which ideas will be generated. This phase is important and creative by itself because it makes it possible to become aware of the systemic aspect of the problem.

Table 2 Reflection axes and associated key points

Axis	Eco-design	Behaviour	Social approach
Key points	Raw materials Fabrication Logistics Use End of life	Learning Incentive Esteem value Sustainable use Information	Needs Aesthetic Works condition Social cohesion

5.3.1 Step 1: Preliminary Evaluation of the Problem

The first step of this phase consists in identifying a global problem on a referent product or service. To do so, a "mind map of problems" was generated from an exhaustive list of generic problem.

This mindmap is suggested from a review of eco-design guidelines, with the objective to have an evolutive mindmap, with a crowdsourcing process [33]. The mind map is structured on three main reflections axes, which are subdivided into different key points (Table 2). These key points lead to the formulation of generic problems and consequently to the required action.

This mind map is structured on two reflections:

- The will of flexibility and liberty for the user. This mindmap actually makes it possible for the user to navigate among problems and to find the relevant problem thanks to the key words.
- The will to orientate at three global reflection axes. The mind map is built on three major axes which correspond to relevant stimuli for responsible innovations: a reflection on behaviour, on social responsibility and on eco-design generic problems.

The first reflection axis, on user's behaviour, appears to be a master piece to allow a strong and breaking innovation, implying the introduction of a completely new product which encourages the user to deeply change his behaviour [16]. The development of this problem made it possible to orientate at a reflection at relation between design and behaviour as environment awareness; this axis was inspired by the reflection of a Design for Sustainable Behaviour [34].

The second axis is the social aspect. This creativity stimulus is important to set up new basis of reflection and to generate a relevant reflection. It gives the possibility to redefine a context, to think about basic needs, which may lead to a reflection not only on the product functionality, but also on work condition and social cohesion problems. Indeed, Josephine Green considers that "a technology really become a motor for growth when and only when it comes with a social innovation. A new technology in an old context does not match" [35].

Finally, the last reflection axis concerns generic problems of eco-design. This axis is structured on the different steps on the product life cycle, in such a way that it is possible to have large enough problems and not deal with a reflection on pure technique.

It is also important to precise that this preliminary evaluation of the problem may be associated with an environmental assessment tool, like ESQCV [36], ATEP [26].

Let's take as example a cellular phone. After a first evaluation, we have determined that the end of life of this product is a fundamental work axis. So we focus on the axis "generic problem in eco-design" of the mind map and on the key point "end of life".

5.3.2 Step 2: Setting Up of the Objects of the World of Problem

Once the global problem identified, the following step is to suggest a creativity space and to define a "world of problem", according to ASIT method, by listing the objects which directly or indirectly intervene on the identified problem.

In this ecoASIT proposition, these objects are defined according to three parameters:

- The life cycle on which they intervene. The global approach of the life cycle is crucial in eco-innovation, in order to correctly identify all the objects which intervene at each phase of the life cycle.
- Their interaction with the problem: the ones that directly intervene (there are the immediate reasons or transfer the problem), or indirectly (there are located in the close environmental of the problem but are not responsible for it).
- Their own characteristics. The objects are differentiated according to their characteristic in order to measure the importance of each one. There are: the "product objects", corresponding to objects defining the product itself (ex: components), or the spatial context (space of use, object located in this space ...); the stakeholders, who correspond to the different actors intervening on the product and who, through the life cycle, must be taking into account in the early phases of the design process [5]; and finally, the victim, represented by the environment, in its literal meaning , that is to say the world that we live in.

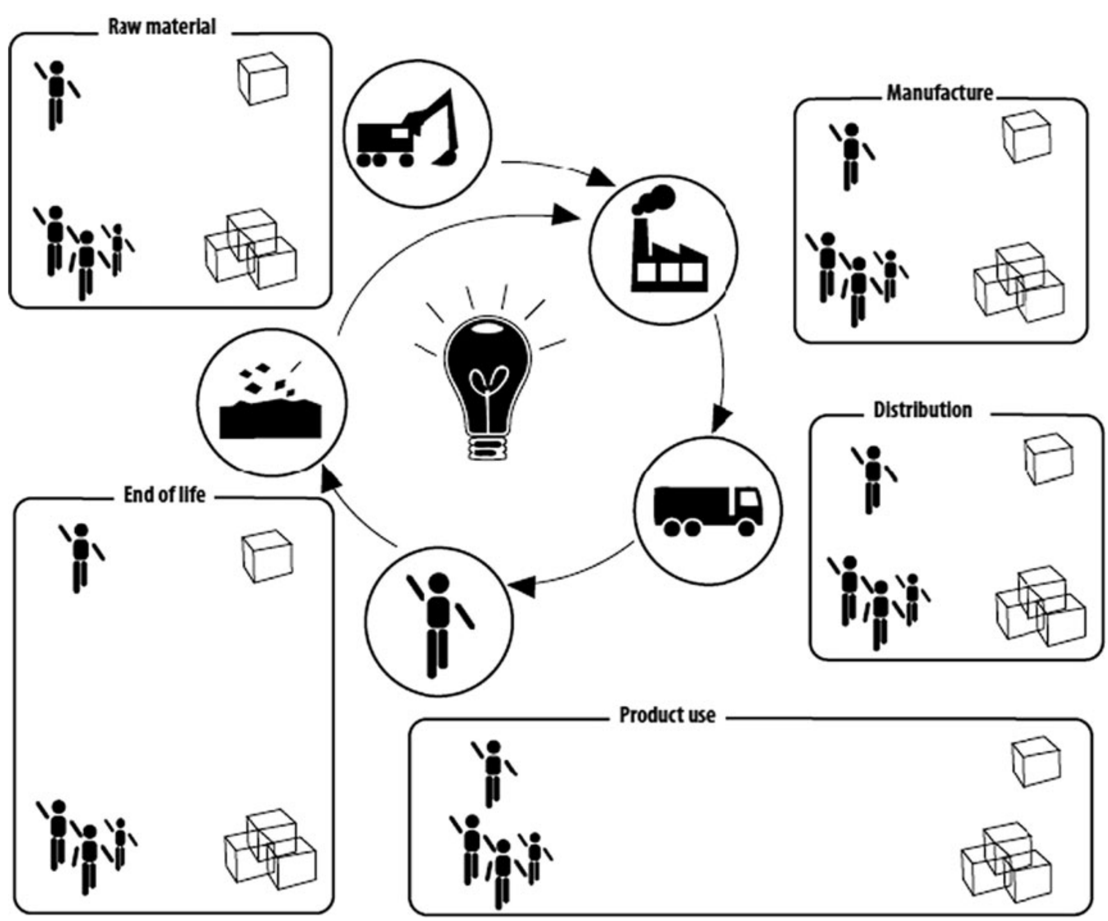


Fig. 3 "Object card" of ecoASIT

Table 3 List of objects of the cellular example

	Use
Product's objects	Direct: SIM card, charger, battery
	Indirect: trouser pocket, use space
Stakeholder	Direct: user, operator
	Indirect: entourage, maintenance
	End of life
Product's objects	Direct: recycling drawer, bin, shop
	Indirect: recycling chain
Stakeholder	Direct: recycler, retailer, recuperator
	Indirect: second user
Environment	Activity, perception, resources, pollution

A preliminary work leads us to predefine objects linked to the environment, in order to facilitate the task on the group during the session.

In ecoASIT, 7 simple objects are defined to describe the victim (in ASIT tool sense), of an eco-innovation problem: natural environment (ecosystem, land use), society (health, ergonomics ...), activity (employment), culture (needs, estimated value), perception (noise, smell ...), resources (energy, water ...) and pollution (emissions ...).

To make this enumeration easier, an "object card" has been defined, which correspond to a basis visually taking back the different lifecycle stages and the different kinds of objects so that the user defines more easily all the objects (Fig. 3). This step is hoped to be collaborative and creative.

In the cellular example, a list of the objects which have an influence of the cellular's end of life has been made, on all stages of the life cycle. For example, Table 3 shows the object for the use and the end of life stages:

5.4 Phase 2: Problem Re-orientation

When passed the first global analysis stage, it is fundamental to focus on re-orientation and definition of the world of problem.

5.4.1 Step 3: Matrix Use

Usually, companies naturally work on eco-design generic problems which are more evident to solve without adding the behaviour aspect or social approach. Relying on Lagerstedt works, which present an eco-functional matrix principle relating the product's functionality to environment, a matrix has been carried out to cross the different "strategic points" issued of the problems' mindmap.

All the strategic points appear on the two axes of this matrix. The target is to cross them in order to determine which ones are interdependent and show a particular interest in the establishment of matchings and re-orientations. Therefore, by crossing "raw material" and "learning", the matrix permits the consideration on the link between raw materials of a product and environment awareness. The same approach is used on the rest of the matrix.

Table 4 ecoASIT re-orientation matrix

	Eco-design	Behaviour	Social approach
Eco-design	Area 1		
Behaviour	Area 2	Area 4	
Social approach	Area 3	Area 5	Area 6

Moreover, specific different areas have been established corresponding to the main reflection axis previously defined (Table 4).

- Area 1: eco-design / eco-design
- Area 2: eco-design / behaviour
- Area 3: eco-design / social
- Area 4: behaviour / behaviour
- Area 5: behaviour / social
- Area 6: social / social

Consequently, a combined problem per area appears, thus defining an identity card of the problem of the product or of the studied service.

In order to carry out a couple of predominant strategic points per area, a simple rating system can be made according to the reflection axis to determine the relevance of the product's "strategic points".

Concerning the example of the mobile's end of life, some problems have been carried out after relating the different key points to the matrix.

Here are the results concerning areas 2 and 3:

- Area 2: end of life/learning
- Area 3: end of life/social cohesion

The matrix has been carried out to orientate the mobile's end of life cycle towards a learning or social cohesion problem.

5.4.2 Step 4: Back to the Problem's Mindmap

Once the couple is determined, the mindmap precisely determines the specific problem and the required action to lead.

Therefore, in this example, the user's behavior is essential so the second area is promoted. This helps the change of the initial end of life problem (eco-design) into a learning problem (behaviour). After familiarizing with the mindmap, the relevant and corresponding problem is identified: "the product does not sensitize to environment". Thus, the required action is "bring the product to sensitize to environment".

5.4.3 Step 5: Back to the Objects

After defining the problem, it can be relevant to come back to the objects' card and to adjust them according to the reflection's reorientation. This list of objects can finally become rather important. Not to make this idea session become to heavy, it is important to select the objects that appear to be the most interesting ones to manipulate. This selection is made by differentiating the characteristics: direct/indirect object and stakeholder/environment/ product object.

Two selection criteria are relevant: the impact of the problem on the object and the industrial influence on the object. No object is deleted, there are just selected to be organized.

To conclude, the two first phases show that the definition of the problem induces a strong relation between the mindmap, the matrix and the objects.

5.5 Phase 3: Generation of Ideas

From this stage, the problem and the objects defining the world of problem perimeter are identified. The aim of this new stage is to induce new ideas with the help of a standard sentence to construct in order to unstructure the problem. The 5 ASIT basic tools have been taken back, making sure that there are organized to be as performant as possible.

5.5.1 Unification Tool

This tool helps the elaboration of the following kind of sentences:

[The Object] will do [Required Action]

So the aim is to take an object and the selected required action from the world of problems, rebuild the sentence and bring out an innovating solution.

In the mobile phone example, the sentence is: The SIM card will bring the product to sensitize to environment.

From this sentence, when a user changes mobile, we could imagine an evolutive SIM card which would help the user to increase the lifecycle of his new phone.

5.5.2 Multiplication Tool

This second tool elaborates the following kind of standard sentence:

A new object of the same type as [the Object] will do [Required Action]

The process described in the previous tool can then start. In the example, the sentence could be: A new object of the same type as the collecting tray will bring the product to sensitize to environment.

We can then imagine an interaction on the benefits of recycling between the tray and the user.

5.5.3 Object Removal Tool

This tool corresponds to the following sentence:

Removing [the Object] will do [Required Action]

In the example, one of the possible sentences would be: Removing the charger will bring the product to sensitize to environment.

We can then imagine a mobile phone including a passive charge mode (dynamo. . .) which will sensitize to renewable energies.

5.5.4 Break the Symmetry

The specificity of this tool is to divide the object in different characteristics to build the sentence (according to the symmetry chosen):

- Space / Time symmetry: at different places / moments, there will be different values for [the chosen characteristic] of [the Object].
- Group symmetry: for many objects of the group, there will be different values for [the chosen characteristic].

In the example, "perception" can be divided in different characteristics such as smell, vision, noise. . .

One of the possible sentences is: At different moments, there will be different values for the "vision".

It can then be imagined an object which will react in different ways according to the moment of the day, relaying environmental information in its environment (such as loud noise) and giving the information back to the user.

5.5.5 Division Tool

To end, this last tool gives this following sentence:

[The object] will be divided in [list of parts] and will be reorganized in time and space.

In the example, the object "shop" can be divided in: welcome, information, sales, repair. . . So the sentence will then be: The shop will be divided in [welcome, information, sales, repair] and will be reorganized in space or time.

We can then imagine that in the shop the reparation is done in front of the customer, to sensitize him to the numerous components and his harmfulness.

5.5.6 Integration Tool

Therefore, a new tool has been carried out to make up what appears to be missing in ASIT: Integration tool. This tool has been carried out because ASIT does not seem to apprehend the global approach of the problem. However, the consequences of the relations between the different objects of the problem (product, environment, user. . .) are modifications on environment and society and so it is important to conceive them [37]. The solution can result of the mix of many stakeholders or of an object with a stakeholder.

Thus, a new tool is proposed to achieve the 5 ASIT tools with a sixth one in ecoASIT: integration tool, fulfilled by the following sentence:

Relating [Object 1] and [Object 2] will do [the Required action].

In the phone example, one of the possible sentences will be: Relating the operator to the second user will bring the product to sensitize to environment.

We can then imagine a system in which the operator facilitates reusing mobiles of his first customers by giving them reduction vouchers or other offers.

6 Conclusion

This article has permitted to define the concept of eco-innovation and of responsible innovation through the literature. Then a list of considerations has been made, in order to point out the different relevant characteristics of an eco-innovation tool. To finish, the last part has developed, through an example, a newly eco-innovation tool prototype.

Nevertheless, it is now fundamental to put the stress on different steps of this tool. The preliminary evaluation of the problem needs to be coupled with a simplified environmental analysis tool. A first tool has been planned thanks to the ATEP environmental impact hierarchy tool but this solutions needs to be deepened.

Similarly, in the idea generation step, it would be relevant to work on "classic" ASIT tools to make them match as well as possible with eco-innovation problems and to think on the relevancy of some objects with some tools. Therefore, the idea selection is a step that remains to be discussed.

For example, a next stage of this research will be to strongly link the mind map and the matrix in order to face with a high number of inter-connecting sustainable problems.

It is now essential to study the first academic and industrial tests in order to draw the conclusions and to judge the relevance of the results. To do so, the perspective of the future works induces to propose an adapted metric to measure the proposed criteria, first to test their validity, and then to be able to use them to measure the relevance of our ecoASIT tool for the experiences that we will lead in industrial conditions.

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Configuration of Complex Custom Products in Early Design Phases Using Dependencies Systems

I. Alexandrescu, H.-J. Franke, and T. Vietor

Abstract This chapter describes an optimized methodology for fast, high-quality design of individual customized products in the field of mechanical engineering. Furthermore, it explains the important role of the configuration in the early design phases. The use of dependencies systems is suggested as a solution for breaking down the product complexity, as well as for the visualization of the product parameters and for the methodical solving of goal conflicts in the configuration process.

Keywords Design methodology · Complex custom products · Early design phases · Product configuration

1 Introduction

In the field of mechanical engineering, small and medium-size enterprises remain competitive only if they are able to develop flexible and efficient custom solutions with relatively short delivering times. In order to achieve high quality customized products, companies have to integrate in their product lifecycle management systems the latest available CAD/CAM technologies, as well as product configuration tools. The use of virtual methods is nowadays a necessity, as they allow optimal decisions to be made in the early design phases and therefore considerably reduce the time and costs of the product development process.

This chapter points out the need for an optimized methodology for fast, high-quality design of individual customized products. Furthermore, it explains how important is the configuration in the early design phases and gives a solution for a systematic solving of goal conflicts resulting from contradictory requirements, by using dependencies systems.

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2 Defining Custom Products

Figure 1 presents product examples based on the customized product palette that has been analyzed in [1]. According to the trends the companies follow in facing the market's challenges, the following classification was done for different types of customization:

- Custom products – new products, developed according to customer's wishes. Unique instances or a very small number of identical units are produced. The costs are relatively high. This chapter concentrates only on this type of products.
- Standard products in their variety – also known as mass production. Prefabricated modules are chosen and positioned into the desired configuration. The result is a large variety of products, resulting from all possible module combinations. Some of the layouts never get to be build. Production costs are not transparent, but the estimations are quite accurate, being based on experience.
- Individualized products – configuration of predefined modules and customer specific adjustments in some defined areas. The basic structure of the product is known. The customization is depending on the contract. The processes are designed for flexibility and therefore the prices and development times are comparable to the ones of the standard products.

3 Problems in Designing Custom Products

This section describes the main problems in designing custom products such as: the drastic requirements' increase over the last decade, the improper usage of available virtual methods and the inappropriate product documentation.

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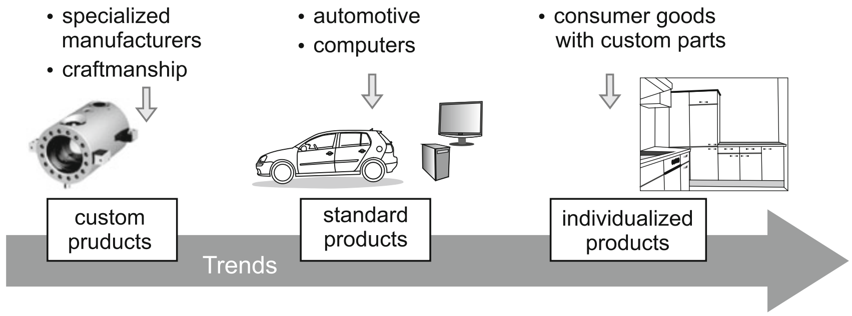

Fig. 1 Trends of the product customization

3.1 Increasing Requirements

On one hand, large and saturated markets in developed countries enforce the production of a broad palette of customized products which satisfy the customers' individual needs. On the other hand, interesting emerging markets together with the constraints of the current economic crisis lead to further differentiation in terms of product functionality and allowable costs. Furthermore, global markets also imply many different standards and norms. Lately these regulations have become stricter due to the worldwide environmental concerns.

The competition of the globalized world, shorter time-to-market and lower prices for the same product quality, drive the manufacturers to fulfill all requirements in the best way to achieve customer satisfaction.

In addition to all these external factors, companies themselves go through constant development, having to keep up with the technology dynamics. Integrating innovative technologies and keeping knowledge up to date while paralleling developing products is nowadays a must for the long term success.

There are many small or medium-size manufacturing enterprises which used to offer in 90% of the cases standard products or their variants. The remaining percentage, dedicated to custom products, has dramatically increased over the last decade. The companies are now more dependent on their custom offerings, therefore facing the need to adopt strategies for developing faster high-quality custom products. Relying just on the few experienced personnel or using several iterations in the development process are no longer economic feasible options.

3.2 Unused Potential of the Virtual Methods

Vanja mentions in [2] that, to be able to meet the stated requirements, companies take different decisions, which can have an organizational or a technical nature. The technical decisions can be: product modularization, integration of new workflows or methods in the product development process and/or systematic use and consequent development of virtual methods such as CAD/CAM systems, simulation or optimization tools, configuration systems and constraint technologies.

When considering custom products, the last point discussed is also the most important one. Over the last 50 years, virtual techniques have been extremely fast developed and intensively used, as they have been proved indispensable in developing complex products. The goal in using computer aided methods is to detect very early faulty designs and to correct them easily.

Common applications are in the aircraft industry [3] or automotive [4, 5]. However, not only big manufacturers, but also small or medium-size enterprises are experts in producing complex custom products. Some examples of such products are shown in Fig. 2.

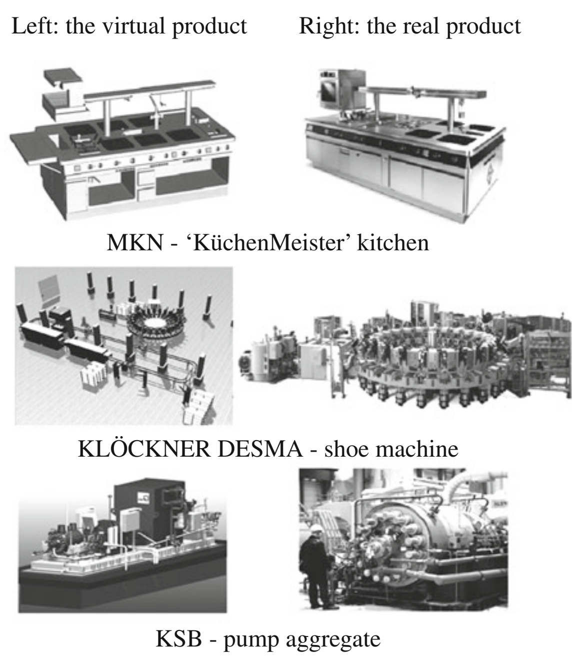

Fig. 2 Complex custom products produced by small and medium-size enterprises

Nevertheless, several problems were generated by the global developed virtual methods:

- The tools are too complex, as they are not developed for special domains of expertise. This results into an inefficient usage of the global functionalities and an uncovered need for particular functions.
- The manufacturers cannot keep up with the update cycles of the software tools. Version compatibility of CAD/CAM systems is also an important issue.
- Incoherent process chains – simulations at different time points do not provide as output the necessary input for the next developing step.
- In praxis there are no methodic approaches that offer support to the automatic transfer of information from the 3D CAD systems. Some proceedings in this field are presented in [6–8]. The innovation potential of these approaches is also discussed in [9].
- Simulation methods are inadequate. It is sometimes impossible to fully describe the problem with the provided tools.
- Communication problems usually arise between the engineer designers that have to work with the systems and have their standard practical point of view and the software developers, who are mainly computer scientists and use a more abstract approach of the problem.

Hence the virtual methods are nowadays in reality rarely used at their true potential [2, 4, 10]. This suboptimal situation can be changed only by means of an adequate methodology for developing new products.

3.3 Unstructured Knowledge Bases

Another main problem of complex custom products is their scattered knowledge base: in each development phase the product knowledge is documented in separate specific systems. The existing PLM/PDM systems are often not properly used and there is seldom a platform available to interconnect or translate the different pieces of information, for a global review or decision taking.

The short time to market and iterative processes between different departments (e.g. between the marketing, sales, project planning and engineering design divisions) cause a bad documentation of the whole product knowledge. Another negative aspect is that frequently the project information and awareness remain by a small group of specialists. They are not reused for later following projects and are unavailable for new employees.

3.4 Need for a New Methodology

Stechert explains in [11] that to deliver a complex product that fulfills the exact customer specifications, a wise management of requirements is necessary, in order to guarantee a goal-oriented product development.

As discussed by Shen in [12], a design methodology is necessary to be developed for the preliminary stage of building design. The methodology should apply a theory of conceptual structure to model building design processes and incorporate the top-down approach of design decisions from a total system point of view.

Gorazd reports in [13] that in the globalized industry there is an increase of interest in collaborative virtual environments, as an alternative or extension to using CAD systems. The high product variety and the mass customization of products demand a collaboration chain, which include customers, managers, designers, manufacturers and suppliers for specific partial solutions.

In conclusion, there is an imperative need for a methodical development of tools that use the potential of current virtual methods to support complex engineering decisions, to integrate the knowledge from the different existing departments and to facilitate product configuration in early design phases. A feasible solution should be formulated interdisciplinary, with consideration to of current thinking patterns of the end users.

4 Better Design for Custom Products

This section suggests a methodology for faster and better design for high quality complex custom products.

4.1 Suggested Approach

Currently, in order to generate an offering for a custom product, the following steps are followed: the client explains the requirements to the sales department; the sales person communicates with the design department and translates the customer requirements, in order for them to generate the desired variant of the product. Then a price is estimated and the client receives an offer. The process is iterative, until the client accepts the proposed solution. These procedures take often a long time and the resulting offers between parties may be less then optimal. Miscommunication between several implicated departments may have an adverse affect on a desired outcome. This topic was previously discussed in the papers [14, 15] by Alexandrescu and Franke.

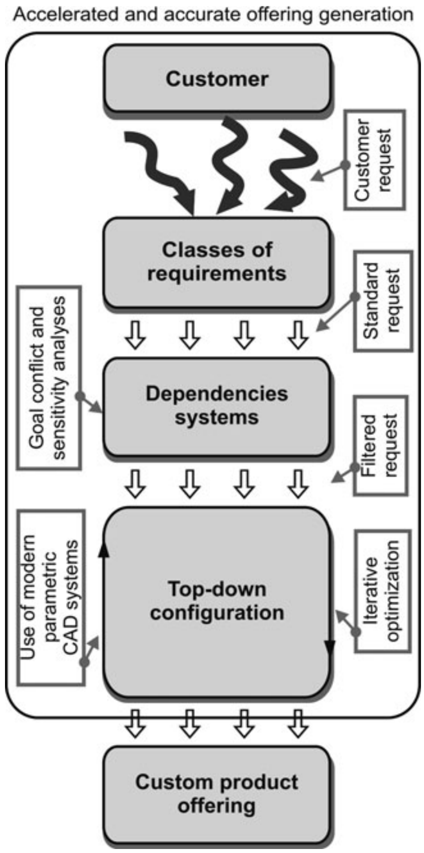

Fig. 3 Suggested solution

In order to shorten the offering generation time, both the client request clarification and the product design process have to be accelerated and the quality of the transferred information has to be improved. The solution is a software system that integrates the product data with existing virtual methods in order to automate the configuration.

Because the custom production is discussed, a completely automated configuration system is not possible. However, it is possible to accelerate and optimize the configuration chain through better requirement definition, product parameter visualization and goal conflict analysis. Figure 3 presents the suggested modules of such software.

As schematically shown, at first the customer request is filtered (e.g. using checklists or templates) and is then transformed into a standard request. Based on this last one, a standard product data set can be loaded and the product parameter dependencies system should be ready for visualization. At this point, goal conflicts can be solved and sensitivity analyses performed. Based on the resulting set of parameters (e.g. technical, geometrical or functional parameters), a top-down product configuration can be carried out. The resulting set of product characteristics is then imported into a CAD system. The automatically generated three-dimensional (3D) parametric model represents about 70% of the solution and has to be adjusted by the design engineer. The final result is a 3D product model that corresponds to the client custom request.

Figure 4 shows a possible implementation of the project goal. The users of the system are marketing personnel and engineering designers. The first ones use the configuration tool as input for the client requirements. As mentioned before, the configuration instrument does not completely automatically generate a product model, but supports the decision process. Different experts can use the system, to decide what the optimal result for the given input is. The task is difficult, as in the case of custom products there are several degrees of freedom in the design process. The sales department, the project coordinator and the design engineering subdivision have to come together on the common platform in order to take complex design decisions.

The configuration software uses the previously built product knowledge base and is integrated in the company's system landscape, sharing information with the existing CAD and enterprise resource planning (ERP) systems. The output of the configuration process is on one hand the product offering: the documentation of the product, pictures, technical description, official offering and on the other hand a 3D parametric associative model that is used by the technical department as initial layout for designing the complete model.

This approach not only shortens the early design development process, but it also reduces the iteration cycles between

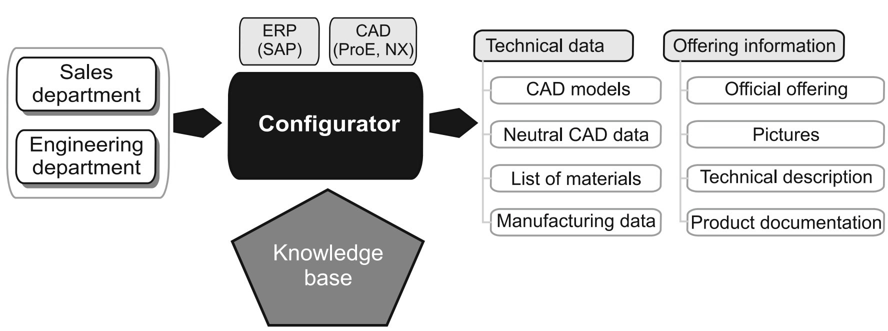

Fig. 4 Implementation of the project goal

the several decision taking departments and consequently assures an accurate generation of the offering.

Three industry partners, two software partners and one research institute are currently involved in implementing and testing this proposed solution. These partners are shortly presented in [15].

4.2 Product Dependencies System

Modeling product dependencies in early design phases is an essential step for the faster and better developing of complex custom products. In early development phases it is important to have a transparent product model, which supports sensitivity analyzes for the product parameters, proposes strategies to find a solution that respects all requirements and also allows an optimization of the solution. Such tools are for example parametric 3D models, pareto methods and, for the first design stages, dependencies systems – which are discussed in the following

The product requirements (either customer requirements, or norms, laws, technical laws or physical principles) and their dependencies can be seen in a form of a complex equation system, for which no solver currently exists. A dependencies system can be modeled to break down the complexity of the product. Its main functions are to link requirements to product characteristics, as well as product characteristics between themselves. This represents a formal approach in recognizing conflicts and in enabling the optimization of product parameters. The integration of such a module in the product configuration chain is presented in Fig. 3.

To systematically collect the product information and then allow a visualization of the dependencies system, the software tool IKSolve was developed. The main tasks of this tool are:

- Systematic collection of parameters.
- Edit operations for the resulted equation system.
- Syntax proof for the given functions.
- Consistency proof of the whole system.
- Import/Export functions, for loading and saving the current parameter configuration, but also for the export of parameters to a parametric 3D CAD model.
- Calculation of parameter values.
- Visualization of the calculation path.
- Calculation and visualization of all product parameters in the form of an interactive graph.
- Visualization of upper and lower dependencies.
- Search, calculation and visualization of just one parameter and its dependencies.
- Plot of the graph corresponding to the equation that describes a specific parameter.
- Analysis of parameter interdependencies.

As shown in Fig. 5, the tool has a textual and a graphical interface. The textual interface allows product information input. This formal input is in form of parameters which have each a name, value or formula, unit, description, minimum and maximum value, raster options, optimization direction and function description (in case the parameter value has to be chosen from a table). Keeping the personal thought patterns, a design engineer can input his knowledge into this tool, which will automatically correct the input (e.g. marking false equation syntax or non defined parameters) and classify the equation system variables into: input variables, target variables, boundary conditions, strong or soft restrictions. This needs to be done only once, in the beginning. The same general product description will be used for all customization processes and can be later adjusted. Here is important to notice that the product description is at a high level. Only the general design rules, important physics laws or calculations used for all custom product design will be documented in the beginning.

The graphical interface permits a visualization of the given equation system in the form of an interactive graph, as well as the visualization of the function's graph corresponding to a chosen parameter.

Dependencies of a certain product parameter can be seen per mouse click, permitting a fast analysis of the system mutation when one variable is changed. The system will be developed so that it is coupled with a constraint solver, which partially automatically propagates the changes, finds and proposes a configuration solution for a concrete parameter input. Hence, the configuration will be not rule based, but constraint based. This permits designing custom products, where any exotic customer requirement has to be fulfilled.

4.3 Example of Gear's Dependencies System

A trivial example of using dependencies systems and monitoring the influences on the product system for one parameter change is shown in Fig. 5. A gear system can be described by the presented equations. The dependencies system can be used to see how the center distance c changes when the addendum modification coefficients x1 and x2 (input values) change. The visualization facilitates a better understanding of the system.

The configured values are than exported into Pro/ENGINEER, to automatically see the changes in the previously build parametric 3D models. An interface to this CAD software was build with JLink, so that the

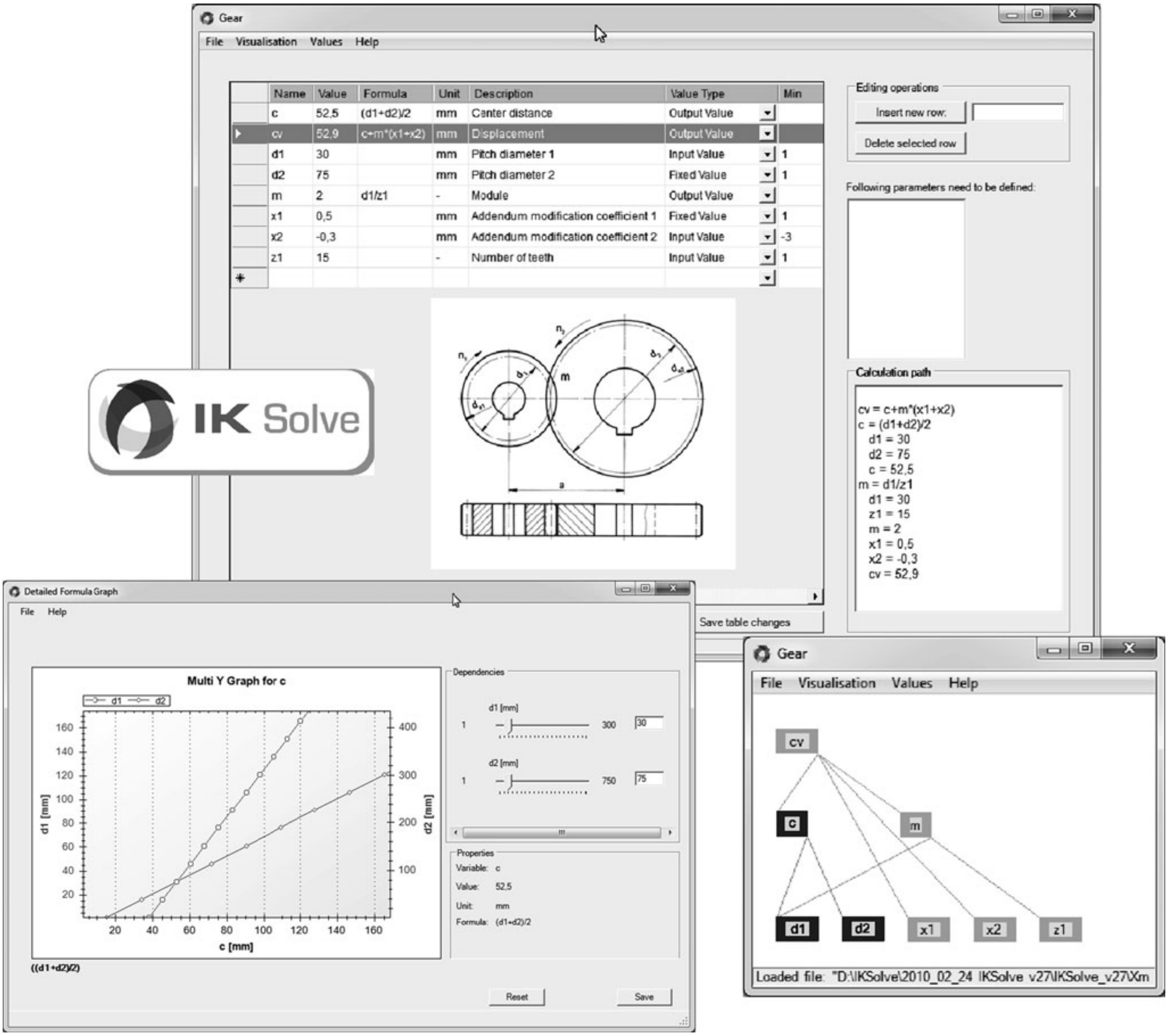

Fig. 5 Trivial example for using the "IKSolve" tool. Visualization of the equation system describing two gears

resulting assembly is automatically build after the import of configured parameters.

This example was given to understand the basic functions of the designed system. In this concrete case, the simple equations that describe the system could be directly given in the parametric CAD system and the result would be similar. However, for more complex products, there are clear advantages of viewing parameter dependencies in such a comprehensible manner and not to encapsulate them in the CAD system. Another important fact is that the IKSolve tool and its interfaces to other software products are not product dependent. They can be used to sustain decisions for the parameter configuration for any type of product. Therefore, a more complex example is given in the following to illustrate these advantages.

4.4 Dependencies System for a Barrel Casing Pump

Boiler feed pumps are essential components of conventional and modern power plants, where reliability, efficiency, and operational flexibility are extremely important [16]. Their power capacities can nowadays reach 45 MW.

A complete KSB pump aggregate (with main pump, gearbox, engine and booster pump), as well as a picture of its 3D CAD model can be seen at the bottom of Fig. 2. The main pump component of the presented aggregate, namely the barrel casing boiler feed pump, is shown in the bottom left image of Fig. 6.

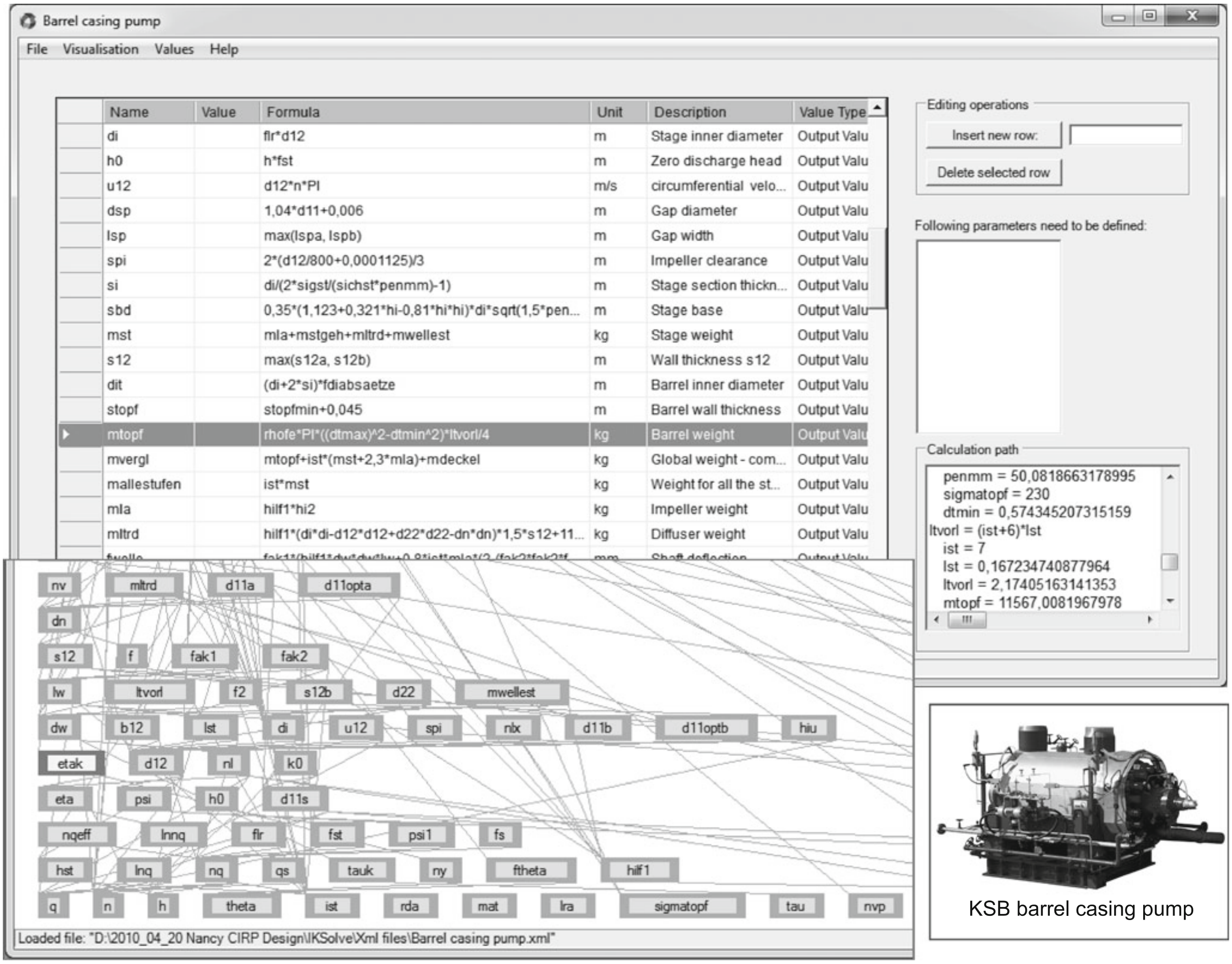

Fig. 6 Extract from a dependencies system for a rough description of a barrel casing pump

Based on laws of nature, similarity relations and the extended hydraulic and constructive experience of Franke – coauthor of this chapter —, a dependency system was defined for a simple parametric model of such a barrel casing pump. The goal was to model the driving parameters and their interdependencies. A definition of a global equation system that is valid for pumps from different manufacturers is not possible, because companies have different strategies in designing these custom products. Parts of the information contained in this dependencies system are strictly connected to empirical design values based on experience.

An extract of the resulted nonlinear equation system, documented with the IKSolve software tool, is presented in Fig. 6. More than 100 Equations were defined, in order to allow the main measurements and evaluation of the simplified model of the pump. In addition to that, restrictions such as minimum and maximum values, as well as information about the optimization direction for each parameter were defined. As seen in Fig. 6, connections between the system components are very complex, and therefore is it very hard to analyze the system without being an expert in the field. Nevertheless, using the proposed software tool, such an analysis can be easier done: each parameter can be selected and calculated; its upper or lower dependencies can be highlighted or shown in form of standalone dependencies graphs; the graph corresponding to the equation that describes a specific parameter can be plotted for analysis.

An evaluation of the discussed complex nonlinear equation system cannot be done automatically through a fixed target function, because the actual weighting of the various objectives has to be done in the context of the considered custom solution.

Dependencies systems can be used in this case to calculate parameters and evaluate their interdependencies. The goal is to help the design engineer to make the right compromises when solving goal conflicts.

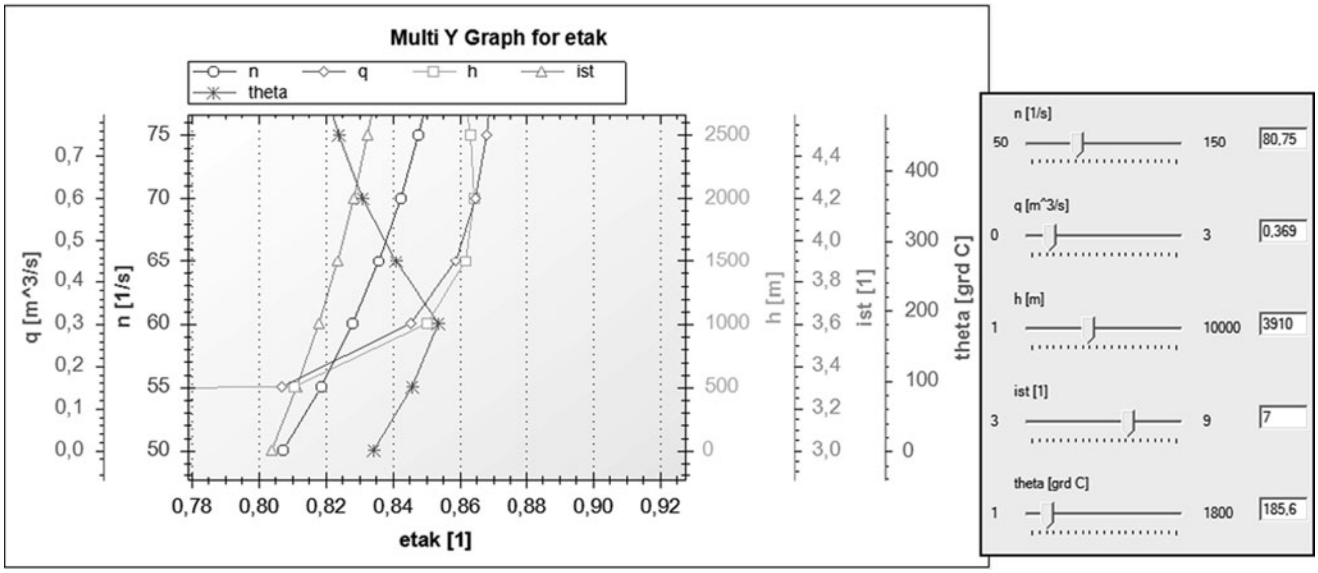

Fig. 7 Graphical visualization of parameter interdependencies for the calculation of the pump efficiency

For example, two highly important parameters which have to be optimized are the efficiency of the pump and the weight of the barrel casing. The efficiency of the pump is significant, considering the aspect of energy costs for pumps capacities of 20 MW or more. The casing is one of the most important components of the pump manufacturing costs, because of its heavy weight and its high material costs. More than that, this component can have long delivery times. Therefore, it is desirable to evaluate this data as early as possible in the design process. The discussed dependencies system describes these two parameters and helps determining their best combination.

On the basis of experience, it is known that in particular the speed and the number of stages have an extreme influence on the efficiency and on the construction costs. Therefore, a variation of these design parameters is a good starting point for an efficient solution strategy. As shown in Fig. 7, a graphical visualization of the efficiency function *etak* helps even less experienced designers to come to this conclusion. On the right side of the picture, the parameters corresponding to the main components of the target function *etak* are shown: e.g. the rotation speed *n*, the number of stages *ist* and the temperature *theta*. The influence of the variation of these parameters on the objective function can be easily analyzed using this intuitive solution.

Based on the constructed dependencies system for the barrel casing pump, other main design parameters such as the stage casing inner and outer diameters or the suction nozzle inner diameter can be analyzed, calculated and respectively optimized.

The configured parameters that refer to the geometry of the pump are then exported to a 3D CAD software system, where a previously build parametric model of the pump adjusts itself according to the new values. This resulted part or assembly is considered the start model for the detailed design process in the 3D environment. The advantage of such an approach is that the global view of the product was previously analyzed and the main design decisions were taken well grounded. Moreover, the functional product dependencies are not encapsulated in the 3D model, but transparently build using the external IKSolve tool.

4.5 Methodical Solving of Goal Conflicts

The design of a complex product with consideration to the multitude of requirements is an extremely challenging task. There is no standard solution when it comes to solving goal conflicts. Existing methods include scenario or portfolio methods, evaluation matrices or virtual simulation methods which use preexisting parametric models controlled by the so called design parameters.

Hänschke explains in [17] that a successful strategy for solving the goal conflicts has to take place in the concept phase of the product development process, before it is too late or too expensive to make changes in the product. The importance of solving goal conflicts in early design phases is also presented by Fischer in paper [18].

The chosen strategy uses constraint methods and dependencies systems to detect and visualize the goal conflicts, and to support finding a solution. This was exemplified for the pump example, where it was discussed how to help solving the goal conflict between greater efficiency and low manufacturing costs using dependencies systems.

5 Conclusions

The constant increasing requirements on custom products lead to many goal conflicts in the design and manufacturing of such products. It is highly important for a basic product configuration to take place in the early design or concept phases, in order to avoid iterations over the whole product development cycle.

A methodical modular solution based on the use of dependencies systems was presented, as a toolset to model the product structure, to support a constraint based configuration and to help the decision making process for solving goal conflicts in this early configuration phase.

Furthermore, the software tool IKSolve was discussed, as an instrument to define, visualize and analyze dependencies systems. Afterwards, a simple gear system was used to exemplify the main functionalities of the IKSolve tool.

The benefits of using dependencies systems in the early design phases were explained based on another example, namely of a custom barrel casing boiler feed pump. Complex products can be modeled in such a simplified manner, that a global view of the product is possible, with its main parameters and conflicting goals. Although this reduced product structure is highly interconnected and there are many conflict goals for the involved parameters, a proper assessment and evaluation can be performed using appropriate visualization techniques. The results can be directly used in parametric CAD models.

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Ecological Aspects in Global Product Development

Integrating Innovations into Vehicle Projects – Towards a Robust "Touch Down" Process

G. Buet, T. Gidel, and D. Millet

Abstract The purpose of our research is to identify the levers, the obstacles and potential variables that help to create a more robust process for integrating innovations into vehicle development projects. The ultimate aim of our work is to help to increase the numbers of innovations providing high added value for the customer that are assimilated into future vehicles.The analysis that we present is the result of an in-depth diagnostic study (40 persons consulted, 80 hof interviews), feedback from five vehicle development projects and detailed analysis of three innovation projects.

Keywords Innovation · Integration process · Robustness, Systemic model · Automotive industry

1 Introduction

No matter which carmaker is observed, it appears that very few innovations actually find their way into vehicle development projects, compared to the number of ideas originally imagined. Yet, the current crisis demonstrates more than ever the need to innovate in a context of economic constraint in order to stand out from competitors and provide more pleasure, more values for the customer and for society as a whole.

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The fact that only few innovations ultimately land up in vehicle projects can be ascribed to various reasons not detailed in the present article. The technical, economic, and also social and managerial aspects of the innovation process has already been extensively covered by other authors [1, 2].

Although it is normal practice to filter out many innovations, it is essential to maintain a certain number within the vehicle development projects. Otherwise, there is a risk of not being able to keep up with market expectations or of being out of step with the competitors' market offerings.

This difficulty of transforming good ideas into innovations that find their place in vehicle development projects may be attributed to the difficulty in converging innovation development with vehicle development. A process that we shall refer to, in the rest of this article, will be defined as the "touch-down", or integration process [3].

This term stems from an analogy that may be made with an aircraft (innovation projects) landing on an aircraft-carrier (vehicle development projects). While "landing", it is essential to specify all the conditions required, to apply all defined processes, but also to know how to react to events in order to make a successful "touch-down".

2 The "Touch Down" Process

2.1 *Characteristics of the "Touch-Down" Process*

In order to keep abreast of the market, carmakers are faced with co-ordinating innovations that have not always achieved a sufficient degree of maturity with the vehicle development projects that are likely to be their platform. The notion of "touch-down" is specified by the integration of such innovations into vehicle development projects [3].

The integration process itself is proving problematical in that new technology fields, organizations and timescales differ considerably from those applicable to vehicle development projects.

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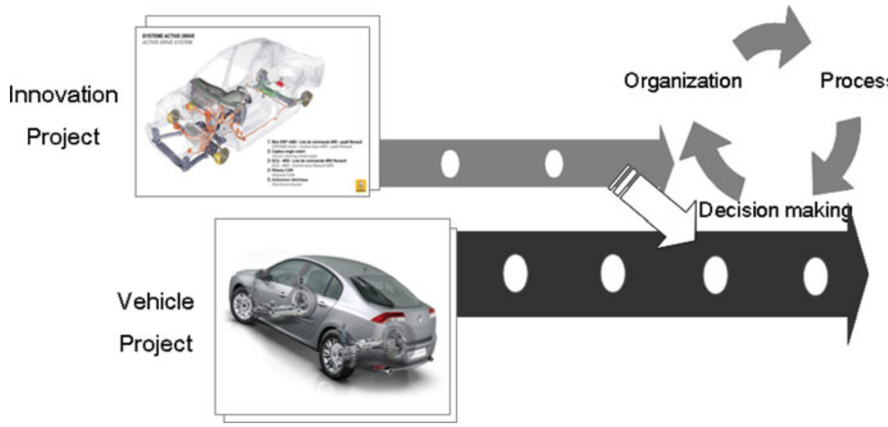

Fig. 1 Example of "touch-down" process

> [. . .] It is a complex process to successfully converge new technology developments (available at the right moment and at the right level of maturity) with product development projects.

The innovation "touch-down" process can be divided into several phases – innovation genesis, selection and, finally, lock-on to the vehicle development project.

The first phase includes identifying and selecting innovations that would appear to be relevant to one or more selected vehicle projects.

This phase comes to an end with the decision to integrate one or more innovations into one or several vehicle development projects. This decision, which is taken sufficiently up-stream in the development process so as to anticipate the risk factor, may be challenged, which is not the case once it has been decided to "lock-on".

Lock-on denotes the notion of effectively mating innovations with the vehicle development project. In our aviation analogy, it would be the hitching of the aircraft to the aircraft carrier with its tail hook.

The decision to lock on may be expressed as the risk of integrating versus the risk of not integrating a given innovation. When the risk of not integrating the innovation is greater than integrating it, the decision to lock on may be considered to be effective. It is preferable, at this moment, for innovation responsibility to be transferred from Pre-project to the Project Development.

To achieve this, it is preferable that:

- Potential earnings be known (response to customer expectations, sales confirmation, profit-earning capacity, etc.)
- The initial planning milestones for the new development are fully achieved
- Initial specimen parts (initial parts from tooling) are convincing.

To our knowledge, there is no formal difference in the integration process as a function of the type of innovation, i.e. incremental, breakthrough or even architectural (innovation resulting from associating certain components rather than a new component design [4]). The only clear distinction is that between the vehicle development project and the innovation project.

We were looking at innovations in the car manufacturer's sense of the term, i.e. a technology or a service that does not exist within the company, although they might already be present at a competitor's or in another market sector.

This definition is in line with the approach described below [5]:

> The fundamental issue of product strategy lies in the motivation with which a company exploits the technologies and knowledge that it has acquired in the past. . . Our analysis is based on product innovation not in relation to what is available in the market, but in relation to the company's previous products – and thus in relation it its current capabilities.

2.2 *Issues Relating to the "Touch-Down" Process*

The chosen method takes in a global system approach and may be expressed as follows: proposal for a methodology to make the convergence process of innovations with vehicle development projects more robust, as a result of improvements to:

- Operational methods in the Innovation, the Technical and the Vehicle Design sectors.
- The process of integrating these innovations (taking into account innovation typology, intrusiveness, etc.).
- Associated instrumentation (tools and selection criteria).

For the purposes of the present article, we have generally used the term "process" in its broadest sense, i.e. including related organisation and instrumentation.

Furthermore, process robustness is a relatively recent topic, notwithstanding Taguchi's work on robustness in general completed for many years [6]. We refer to the following definition to qualify process robustness [7]:

> Capability to deliver expected results in the presence of unexpected adverse factors.

In our case, this means delivering an optimised "touch-down" process that is fully able to withstand adverse factors, whether these be internal or outside the manufacturer's sphere.

3 Analysis of Five Vehicle Projects

The concept of "touching down" or integrating innovations in vehicle development projects was analysed from a vehicle project standpoint by tracing the presence of innovations and the appearance and disappearance of certain innovations throughout the vehicle design and development phases.

For the purposes of our study conducted on five recent Vehicle Development Projects (one of which was launched on the market beginning of 2010, one was discontinued and three are still under development), the innovations were classified according to the manufacturer's innovation typology:

- Technical/Product/Service innovations.
- New technology innovations.
- Other innovations (generated by the Technical departments, suppliers, etc.).

The innovations listed at the start of the vehicle development projects were recorded. We then tracked the flow of innovations (discontinuation of some, adoption of other new innovations) during the pre-project and development phases of each of the vehicle projects.

We targeted three vehicle projects in particular, tracing the innovations from the Innovation Seminar, held immediately prior to the formal Project start-date ("Intention" milestone), which aims to re-define and prioritise potential innovations to be integrated into vehicle projects, to the Contract milestone, which marks effective start of the development phase and is followed by industrialisation. We chose the Vehicle Contract milestone as the reference milestone, because, from this stage, in principle, the vehicle content is frozen until the launch phase. The average time between the formal vehicle development start-date and the Vehicle Contract milestone is 2 years; this milestone marks the manufacturer's firm commitment to the project with respect to quality, costs and timescale.

Our study revealed that between 25 and 50% of innovations identified at the end of the Innovation Seminar (after prioritization) find their way into the vehicle project by the Vehicle Contract milestone stage. However, this does not mean that the vehicle will have a low innovation level when it is launched; although some innovations are eliminated during the pre-project phase, others emerge as a result of market developments, customer expectations, competitors' activities and regulations, etc. In addition, some innovations are abandoned at a certain stage, only to be "resuscitated" later on, for the same reasons as for other new innovations (changes in regulations, competition, etc.).

However, this analysis raises the pertinence of the innovation integration process, because many innovations that ultimately land up in the vehicle development projects have not gone through the standard innovation process, which, in theory, consists in identifying the innovations to be incorporated 2 years prior to the Contract milestone.

The factors that engender this situation may be:

Internal

- Technical constraints of integrating certain innovations.
- Economic evaluation of the innovation reveals no return on investment.

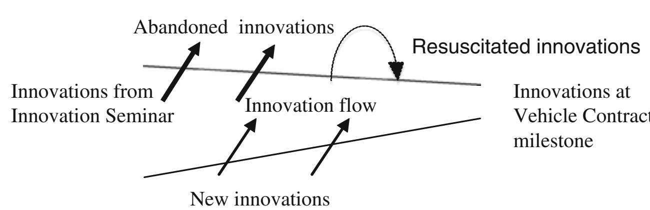

Fig. 3 Innovation flow from innovation seminar to vehicle contract milestone

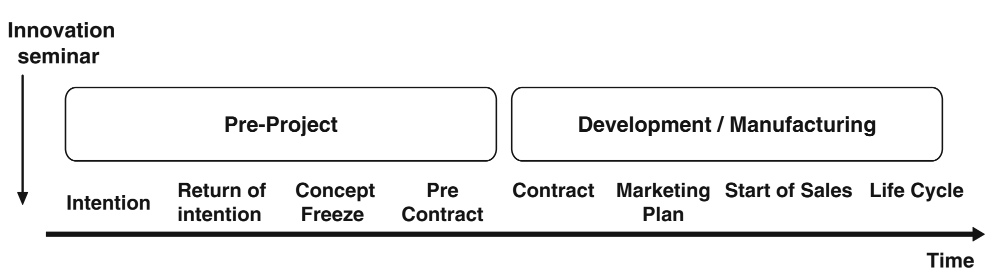

Fig. 2 Vehicle development project, with milestones

- A high degree of uncertainty (cost, volumes, potential customer value, reliability, etc.), which makes it difficult to make a decision at least 2 years up-line.
- Difficulty in developing the innovation in timescales compatible with vehicle development timescales.
- Innovation maturity [8]. In general, innovation definition progresses from a general idea to a precise description for a technical solution in parallel with vehicle development progression. From a certain stage onwards, a low level of maturity may cause a lack of confidence' in the innovation and hence a reticence to integrate it in vehicle project(s).
- Lack of support from Top Management.
- Inability to anticipate requirements upstream (changes in regulatory requirements, etc.).
- ...

External

- Sudden, unexpected changes in the market.
- Abrupt changes in regulations (environmental, safety, etc.) making it necessary to discontinue certain innovations or integrate others.
- In the event of co-innovation (steadily increasing over recent years), partners' level of commitment.
- ...

This global analysis suggests the need to work on a convergent "touch-down" for innovation development and vehicle projects.

With a more robust "touch-down" process, it would be possible to increase the number of value-added innovations that can be integrated in vehicle projects. However, a robust process does not necessarily mean a lack of flexibility; indeed, a more flexible "touch-down" may enable innovations to be integrated at a later stage, if they are not too intrusive. In addition, the innovation development timescales may be very different, depending on their field of application (safety, performance, environment, passenger comfort). Some innovations may be developed over very short periods and be integrated at a late stage without any risk to vehicle project quality, if their intrusiveness is extremely low. They can be handled outside the vehicle project cycle.

4 Research Methodology

4.1 Introduction

Our methodology included six stages:

1. Bibliographical research (exploratory rationale, inventory, options)
2. Detailed diagnostic study, identification of initial solutions for progress
3. Modelling in order to gain a better understanding of the "touch-down" process
4. Descriptive analysis of three real cases of innovation "touch-downs", to enable comparison of the key points of the diagnostic and the modelling with actual cases
5. Formalisation of a "touch-down" theoretical model
6. Experimentation. Specification logic for environmental innovations applied to future vehicle projects

The work presented in the present article corresponds to stages 1 to 4. Formalisation of a theoretical model is currently only at a preliminary stage and testing of innovations associated with environmental issues will be the subject of subsequent research.

4.2 Results of Detailed Diagnostic Study

4.2.1 The Persons Consulted

Forty persons were consulted, representing 80 hof interviews. Those consulted currently played a role in the "touch-down" process, i.e. they were new technology project managers, vehicle development project managers, financial project managers, technical managers (vehicle architecture, electronics, etc.), representatives of Pre-projects and of Marketing. High-level decision-makers were also questioned as part of our diagnostic study.

The aim was to gain a closer insight into real-life practices and at the same time to bring to light any differences between the official message and local perceptions.

4.2.2 Interview Guide Structure

The interviews were conducted in a semi-guided manner.

The subjects covered were:

- Innovation management by the carmaker, as perceived by the persons consulted
- Analysis of the current "touch-down" process for innovations integrated into vehicle projects (strong points, areas for improvement).
- Feedback on some specific cases as experienced by the persons consulted.

4.2.3 Diagnostic Summary

In summary, the diagnostic study revealed four major points, outlined below, about which there were contradictory opinions:

- *Innovation Requirement:* some of the persons consulted were of the opinion that the requirement should be relatively broad, providing a mere framework for the innovation specification and not limiting the area of investigation. However, others believed that the requirement should be reduced to the bare necessities, thus limiting the area of investigation quite early on in the process in order to maximise its chances of success. It should be noted that not all innovations are derived from a formal innovation requirement; many arise spontaneously (proposals from the Technical areas, R&D and from suppliers).
- *The "Touch-Down" Process* must make reference to design/development standards, without being overly rigid. Excessive standardisation is perceived to be an obstacle to innovation, preventing good innovation opportunities from being taken up. The process should provide structure, but at the same time be flexible and able to be adapted to the different types of innovations – a single standard would not easily meet this requirement.
- *Evaluation and Selection Criteria*: the advantage of the criterion of cost-effectiveness (cost/value) that is widely used to decide whether or not an innovation should be assimilated into a vehicle is that it is consensual and easy to appropriate, particularly as the content and calculation methods for both costs and value criteria have recently been considerably optimised. However, cost-effectiveness reveals its limits in certain cases and sometimes needs to be completed by additional criteria relating to impact on image, contribution to corporate strategy, need to comply with regulations or to be in phase with the market and keep abreast of our competitors' market offerings.
- *Parties Involved*: contradictions appear in particular with respect to the teams in charge of design and development of an innovation. For some of the persons questioned, it is a good thing that these teams are not the same – they believe that it is necessary for team members working in upstream phases, where the creative input is high, to be different from those working downstream, where the final aim is very concrete (to industrialise the innovations). For others, the weak point of the "touch-down" process is the split between the upstream and downstream phases – they feel that it is essential to maintain the same team (or some of the team-members) throughout the entire innovation design and development phase.

4.3 Model Filters Employed

The aim of the model filters we used for our analysis was to achieve a better understanding of the "touch-down" process by describing:

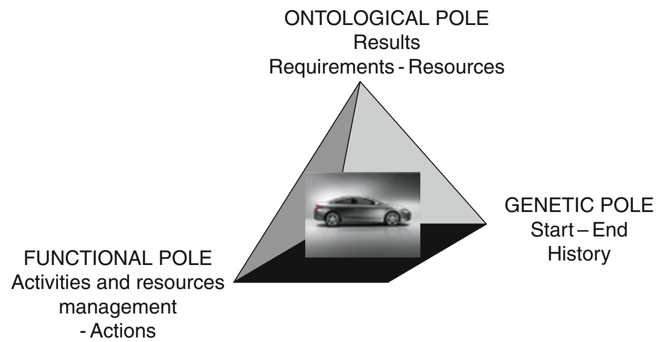

Fig. 4 Presentation of the OFG filter

- The "touch-down" process itself and its complexity.
- Factors that initiate "touch-down" and how changes to these are taken on board.
- The most appropriate evaluation and decision-making tools throughout the process.
- The importance of key players or groups with specific roles to play
- Appropriate timing and focus on the effort required to ensure successful integration.

This analysis is based on theoretical models [9, 10].

The model filters used to gain a better understanding of the innovation "touch-down" process are:

- Operational, Informational and Decision-making (OID)
- Ontological, Functional and Genetic (OFG)

By using the OID and OFG filters we were able to make a comprehensive analysis of the innovation "touch-down" process, without omitting elements which might have appeared to be minor at the start of the study.

The "touch-down" process involves a complex organisation including several in-house Divisions (essentially R&D, Pre-Product, Pre-project, Vehicle Design, Engineering). In addition, it is not limited to the company, but has a wider scope, including, in particular, regulatory organisations, suppliers and other partners (in the academic sphere, etc.).

Many control structures are involved throughout the "touch-down" process – one is the Innovation Seminar (held prior to each vehicle project start-date) and another the Innovation Strategy Committee (arbitration and decision-making body, whose role is to submit innovation strategy to Executive Management for regular validation and to define the annual Technology Plan).

The "touch-down" process is also constructed with reference to several of the manufacturer's own specific reference standards (design, development, quality standards).

All the above factors helped us to analyse in more detail the "touch-down" process for two specific innovations, EasyDrive and EasyNav.

5 Examples of Innovation "Touch-Down" in Vehicle Projects

5.1 EasyDrive and Easy Nav

Three instances of innovation "touch-down" in vehicle development projects were analysed and these real-life cases were compared with the research hypotheses and models. In this way, we produced three "touch-down" pictures to provide an empirical description, using a modelling framework as a filter.

We present in Table 1 two different cases; the first, EasyDrive is the result of a technology push and the second, EasyNav, was generated by market pull and was part of an "Open Innovation" process [11].

5.2 Lessons Learned from the Cases Presented

These two cases illustrate very different innovation "touch-down" processes, particularly during the initial stages.

The key points to be noted from these two cases and from our diagnostic are presented in Table 2.

6 Discussion: Interpreting the Research

6.1 Potential Improvements to the Innovation "Touch-Down" Process

Ideas to improve the way in which innovations are assimilated into Vehicle Development Projects were formulated following the extremely detailed diagnostic study (40 interviews) and were developed after the work carried out on real innovation cases and analysed using a reference standard model filter. At this stage, the hypotheses expressed should not be considered to be recommendations for a more robust convergence process – they are factual observations based on a large number of interviews, bibliographical research and real-case analysis. They will undergo additional validation, notably during the specification phase – an experimental protocol will be defined to test the pertinence of these hypotheses on innovation projects undergoing final "touch-down", i.e. convergence with a vehicle project.

In summary, in order to improve robustness of innovation convergence with Vehicle Development Projects, we have marked out four fundamental hypotheses:

- *Need to structure requirement formalisation* according to a partnership rationale, involving both innovation players and vehicle project players. It is necessary to accurately define the activities expected by Vehicle Projects and to identify the innovations that allow these goals to be achieved. This clarification must enable the people responsible for designing the innovations to appropriate the vehicle projects' expectations by limiting the area of investigation to the bare minimum. The objective is to define a simple strategy that is carried out and adjusted by means of regular feedback between the innovation project players and the vehicle project players. Methods such as Quality Function Deployment [13, 14] may provide a better understanding and deployment of the requirement.
- *Need for one or more generic "touch-down" processes*, selected as a function of the specific type of innovation (level of intrusiveness in the vehicle project, need to respond swiftly to market demands, etc.) and taking into account the key events of touch-down (firing slot). These processes would form a framework that should be adaptable to each specific case.
- *Need to facilitate decision-making,* based on information from appropriate evaluation and decision-making criteria related to the concerned field (example: safety, passenger comfort, environment/CO_2) and manage risk by working on different scenarios relating to volumes, costs, income and profit-earning capacity. It is essential to have, at the opportune moments (when arbitration/decisions have to be made) pertinent criteria and data (including the associated level of risk), by sufficiently anticipating innovation project design/development constraints – principle of irreversibility [15, 16]. This should help towards more robust decisions being made [17].
- *Need to identify the players and define their role* ("project bearer", "sponsors", "touch-down network", focusing effort – "running start" to enable convergence of all players involved. A key component is the complementarity of disciplines of the persons forming part of the "touch-down" network.

6.2 First Approach to Establishing an Innovation "Touch-Down" Model

At present, there is an identical "touch-down" process for integration of all innovations within Vehicle Projects, no matter what type. However, innovations are, by their very nature, unique in character, which could result in defining numerous "touch-down" processes. This would run counter to the need for standardisation.

Between these two extremes, it appears to us to be necessary to have two or three "touch-down" processes and

Table 1 Comparison of the two cases (EasyDrive and EasyNav)

EasyDrive	EasyNav
Demand	
– Desire to set the manufacturer apart in the active safety field – An innovation that significantly changed key vehicle units (steering, chassis, suspension) gave rise to several research projects in the 1990s – These research projects, which to date had not been integrated in any vehicles, re-emerged within a vehicle development pre-project that was short on innovations.	– Initial opportunity came from the marketplace with the explosion of nomad navigation systems at very competitive prices, completely short-circuiting the automotive sector, which offered much more expensive integrated systems. – Without any requirement being expressed at the outset, an in-house Technical team conversant with this technology grasped the opportunity to work on low-cost navigation solutions.
Integration (“touch-down”) process	
– Development: innovation initiated by Technical areas: from the outset, accent was laid on operational reliability with the aim of eradicating all potential risks. – Convergence: choice of technical solution. Production of prototypes to validate the solution and appropriation by key players. Discovery during the process (“Design Thinking” principle, [12]) that over and above active safety, driveability was revealed by the demonstrators to be a major aspect of differentiation. – Integration of the innovation into the vehicle project: the innovation was introduced at an early stage, because it had a high intrusiveness level. The innovation was locked on to the vehicle project before the anticipated vehicle milestone. Excellent co-ordination between the different in-house entities and the key supplier. – The innovation was developed within the vehicle project: innovation development followed the set milestones, with good co-ordination between the parties involved (in-house entities and major suppliers). The quality of the innovation led to the manufacturer being awarded an “Innovation Trophy” in 2007.	– Development: the Technical team made contact with several external companies specialized in nomad navigation systems. Intensive testing of the envisaged technical solutions was conducted in collaboration with the target companies, to identify potential solutions and to draft a requirement specification. – Convergence: production of very convincing demonstrators, which facilitated decision-making. – Integration of the innovation: consultation of all vehicle projects with the aim of integrating this innovation. From the start the innovation was designed to be transversal and was able to meet the technical constraints of different vehicle projects. – Development of the innovation within vehicle projects: no development in the strict sense of the term – it was a question of integrating a product into the vehicle projects, each of which had specific technical constraints that had previously been identified. This explains the extremely short development timescale compared to normal standards. It was possible to integrate the innovation at a very late stage because of its low level of intrusiveness; furthermore, a more conventional back-up solution existed.
Evaluation and decision criteria	
– Great uncertainty concerning the cost/value ratio of the innovation throughout the vehicle design and development phases (cost changes, changes in volumes, expected added value for the customer, etc.) which made it difficult to make a decision. Development of the innovation within a single vehicle project restricted potential volumes. – The normal evaluation criterion (cost/value) revealed its limits, due to very high initial investment (complexity of the innovation) and the low level certainty regarding sales assumptions.	– The cost/value evaluation was extremely advantageous for the manufacturer. Potential gains were proven (declared customer expectations, volumes, etc.). When the project was presented to Executive Management, the risk of not implementing the innovation was greater than the risk of implementing it. – Beyond the economic aspect, the first milestones of the innovation programme plan were all achieved and initial samples (initial parts from tooling) were convincing. – The innovation became a vital necessity in the economic context and was welcomed by the network.
Roles played by the participants	
– Project bearers: the initial bearer had strong technical credentials and internal support. The development pilot also enjoyed in-house renown for his technical and managerial skills. – Sponsors: the innovation received support from Top Management from the outset, which was essential when there was major uncertainty concerning its profit-earning capacity. – “Touch-down” (convergence with Vehicle Project) network: an external consultant was sought during the pre-project phase to co-ordinate the different technical areas and to manage overall project progress towards convergence. Subsequent transfer between the pre-project and project phases went smoothly. Certain players in the pre-project phase continued to be involved until the industrialization phase.	– Project bearers: a small, close-knit team from the start operating according to in-house entrepreneur principles. The team itself “sold” the innovation directly to Vehicle Projects. – Sponsors: during the pre-project phase, the team benefit from a “Business Angel” which meant that the necessary budget was made available. When the innovation entered a more practical phase (demonstrators, business case creation, etc.), Top Management imposed the innovation on Vehicle Projects. – “Touch-down” (convergence with Vehicle Projects) network: this network included persons who were extremely complementary, between the manufacturer’s internal team which had worked on the project, representatives of the selected supplier who formed an integral part of the project and academic circles which had been consulted at the outset concerning work methodology. Furthermore, there was no “break” between the pre-project phase and the development phase; the team remained virtually the same.

Table 2 Lessons learned from EasyDrive and EasyNav cases

Issues	Lessons learned
Innovation reference standard	
– There is a single innovation management standard that makes no distinction between the type of innovation to be integrated into the vehicle development projects.	– The cases presented and the diagnostic demonstrate the need for a flexible and adaptable "touch-down" process. This could lead to proposals not for a single, unique "touch-down" process, but two or three processes as a function of the innovations being handled (intrusiveness, etc.)
Origin of the innovations	
– Certain very pertinent innovations (such as EasyNav) initiated by the Technical areas may not be taken up and/or not enjoy the necessary management support, because they enter the manufacturer's Technology Plan at a late stage, or not at all.	– It is necessary to strengthen the links between the Technical areas, whose prime function is not innovation, but who may generate innovations by taking up opportunities, and the areas responsible for generating and managing innovation. Links are necessary for better communication between these two "worlds", via innovation-bearers and sponsors.
Moving the innovation downstream	
– In certain cases, there are problems of loss of skills, a "break" between the pre-project phases and innovation development, which could have a strong impact on the "touch-down" process. These problems mainly result from the fact the upstream and downstream teams are, in theory, different and do not provide strong management of this transition phase.	– The two cases presented demonstrate the importance of a well-managed transfer between the pre-project phases and the development phase. All or some of the innovation project team members remained until industrialization and launch. Without having to keep the same team from start to finish, it would appear to be necessary to keep at least one or two team members to provide project continuity and a give "running start" for successful convergence between the innovation and the target vehicle development project(s).
Innovation transversality	
– For one of the innovations presented, there was a lack of transversality. Yet, one of the keys to the success of an innovation is its transversal nature (ability to be integrated into several vehicle development projects). This allows significant volumes to be generated, which helps to ensure the profit-earning capacity of the innovation and make it more visible to the customer. In certain cases, not deciding on or not anticipating innovation transversality may have en extremely negative impact on an innovation's profit-earning capacity.	– Innovation transversality, particularly if the innovation requires major investment, must be thought about in the very early stages. Technically, the constraints of rolling the innovation out to several vehicle development projects with, potentially, very different architectures must be taken into account from the outset. The cost of "re-contextualizing" an innovation may be extremely high, sometimes requiring full system redesign. However, integrating all the technical constraints inherent in each target vehicle project can compromise innovation transversality.
Managing risk and projection into the future	
– The case analysis and diagnostic demonstrates the great difficulty in dealing with risk concerning evaluation of the cost, volumes and profitability of innovation projects. These evaluation criteria appear to change significantly during the project design and development phases, making decision-making difficult.	– The innovation must be globally evaluated with respect to what it can contribute to the project and to the company in terms of profit-earning capacity, but also image, contribution to strategic objectives, etc. Sophisticated decision-making tools may help, but they will never resolve the risk inherent in the decision to innovate, particularly as some criteria are difficult to quantify (impact on brand image, etc.). Moreover, improved projection into the future should allow learning curves for cost and volume assumptions to be defined further upstream in the process.
Management support for innovations	
– Some innovations may suffer from lack of support from Top Management (at the start of an innovation project, or during the entire convergence phase), which could lead to them not being considered, despite their pertinence in economic and strategic terms.	– It appears to be essential to have the support of the "bearers" and "sponsors" (generally Top Management) of an innovation considered to be relevant by the company for it to succeed. These bearers and sponsors may support innovations during the decision stage by top management.
Co-ordination between technical areas and implementation of a "touch-down" network	
– Co-ordination between technical areas sometimes raises problems in the upstream phase. The "touch-down" process needs to be prepared and anticipated very early. The difficulty of converging all people involved in order to successfully integrate the innovation in the target vehicle project(s) is sometimes underestimated.	– It is sometimes necessary to call upon a neutral party, or even an outside consultant to provide co-ordination between the technical areas. Moreover, it is essential to form a dedicated network of people to ensure successful final "touch-down", i.e. convergence with the vehicle project. It should be organized, structured and "open".

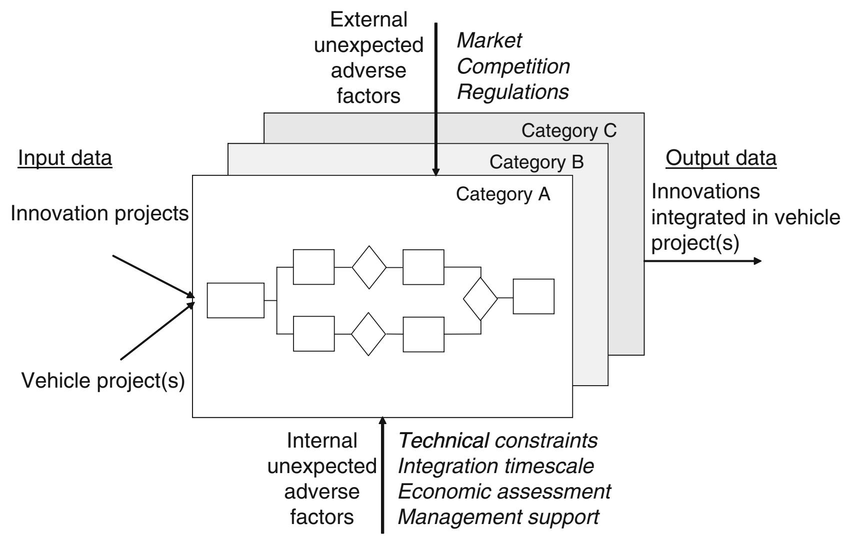

Fig. 5 Touch-down process as a function of the type of innovation

not a single process, to be applied depending on the type of innovation (A, B or C). The following diagram illustrates this proposal Fig. 5.

This outline model constitutes an initial idea for further development. This, of course, presupposes that classes of innovations are defined according to a multi-criteria approach based on the innovation source (in-house, external, etc.), how intrusive it is, its importance in terms of vehicle project and/or company strategy, its capacity to be deployed on several vehicle projects (including associated constraints), the required time-to-market for the innovation (to comply with regulations, respond to our competitors, etc.).

Abundant literature exists on the methods of classifying innovations in relation to the specific objective: impact on integration with vehicle projects ([18, 19]).

7 Conclusion/Perspectives

The present article identifies the essential elements that typify the issue of “touch-down”; it identifies several concepts (“lock-on”, “touch-down network”, etc.), which require further in-depth study. The purpose of this work is to help to increase the number of innovations with high added-value for the customer that find their way into future vehicles.

Our detailed diagnostic study and analysis of three real innovation cases have brought to light some major factors which could have an impact on “touch-down” robustness – the need for a formal structured requirement for the people dealing with innovation projects and those in charge of vehicle development projects, an adaptive process or processes depending on the type of innovation, definition of appropriated evaluation/decision-making criteria for the concerned people plus management of risk uncertainty, and the need for key players (“innovation bearers”, “sponsors”) to “buy into” the innovations in order to facilitate their final implementation.

These different variables enable us to act on the robustness of the “touch down” process, not from a statistical point of view, but from a process, an organisational standpoint.

Application of these hypotheses for improvement should help to make integration of innovations into the manufacturer’s future vehicle development projects. However, this research programme is only at the conception/description stage. All the factors driving robustness will have to be detailed and validated. The experimental protocol and the “touch-down” model(s) that will emerge will embrace all the lessons drawn from our diagnostic and from our real-case investigation. Following an experimental phase, these lessons may result in a list of recommendations to ensure successful touch-down, the aim being to propose one or more very specific models to in-house clients working on innovation projects or vehicle development projects.

Then, the aim is to move on from the descriptive stage to formulation of a specification: the hypotheses and models developed will be tested for integration of innovations into future vehicle projects, which may be Internal Combustion Vehicles (ICE), Hybrid Vehicles (HV) or Electric Vehicles (EV). The “touch-down” models to be developed will have to include the specific features of these markets, in particular for the electric vehicle, which introduces a new development logic [20].

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Requirements and Features Clarifying for Eco-Design Tools

F. Vallet, B. Eynard, and D. Millet

Abstract The issue of requirements of eco-design tools appears regularly in eco-design literature. Helping actors from design teams to structure their practice of eco-design is indeed a key topic in engineering design. So far authors have high-lighted various aspects of these context-related requirements. Our approach, based on actual utilization of existing tools, raises the following question: what is a good eco-design tool? How can it be characterized? Our original contribution is firstly to cluster requirements in two structured categories taking into account process and results on the one hand, cognitive and social aspects of eco-design practice on the other hand. Requirements are tested with experts in academia on four eco-design tools. In order to analyse how requirements match different tools, a specific framework is also created. Objective evaluation by the researcher is combined with subjective perception of experts. First conclusions about assessment of creative outcomes, usability of tools and confidence in results are presented.

Keywords Eco-design tool · Requirement · Creativity · Context · Confidence

1 Introduction

Nowadays companies are more and more aware of the potential benefit of developing environmentally sound products. Legislation is of course a powerful driver. But beyond that consideration, integrating environmental factors can be considered as a business opportunity leading to decreased costs, increased customer satisfaction and even favour innovation [1]. The eco-design framework described in ISO 14062 is progressively shifting to a sustainable design framework [2]. Within the dynamics of integration, it is necessary for actors in companies (in a broad sense) not to consider the environment as a constraint any longer, but as a real value [3]. There is therefore an obvious need to bring substantial change in organizational and learning structures. Design methods used by design teams, as well as tools supporting those methods also have to be renewed and improved. In the recent years a large number of tools have been created and tested in industry. Surveys and interviews from literature state that eco-design tools tend not to be used by designers in their daily work [4, 5]. Consequently many requirements on both usability and appropriateness of tools are expressed [4, 6, 7]. Lindhal [4] emphasizes the importance of the context in which a method or tool is used. Designer's experience and knowledge define, for instance, a specific context of use. With regard to human attitude of designers towards eco-design methods and tools, several other key issues are also mentioned by authors:

- A need to have confidence in methods and tools [5], to cope with uncertain information [7].
- A search for a "higher degree of work satisfaction" [5].
- The importance of collective memory of companies, as well as individual memory of the designer. According to Lindhal, the use of methods and tools in companies contributes to build "know-how backups". With regard to individual use, adopting a new method implies giving up a former one. Nevertheless an abandoned method is never forgotten. It is "consciously or subconsciously integrated by the designer into a new method or tool" [5].

Our approach based on actual utilization of existing tools finally raises the following question: what is a good eco-design tool? How can it be characterized? Throughout this

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paper an attempt will be made to answer this question considering performances of eco-design tools in a broad and original sense.

The research method will be exposed in Sect. 2. Requirements from literature are integrated into a newly organized set presented in Sect. 3. In order to test those requirements an experiment in redesign of a simple product was conducted (Sect. 4). The first group of results is presented in Sect. 5. These are discussed and put into perspective of future works in Sect. 3.

2 Research Method

It is our belief that a process of transformation is induced by use of eco-design methods or tools. This transformation between states 0 and 1 affects both environmental performances of products and, from a human point of view, levels of knowledge and confidence of actors (Fig. 1).

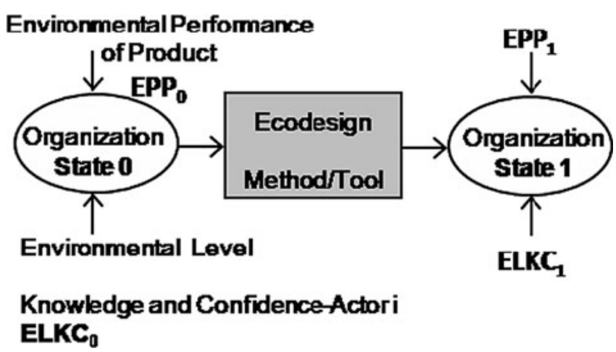

Fig. 1 Transformation process around eco-design methods or tools

The proposed research method is expected to be comprehensive since it is not only centred on an analysis of results, but also on an in-depth understanding of eco-design process from a cognitive and social point of view.

Our analysis is based on two complementary approaches (Table 1). On the one hand, participants provide a judgement, or perception, of each eco-design session they were part of. On the other hand eco-design sessions are coded and analysed on a more objective basis by the researcher. The latter analysis is still in progress.

2.1 Detailed Framework

A case study partly defined in [8] was conducted in academia with ecodesign experts in March 2009.

On this case study four eco-design tools were tested. Of these, three are eco-design guides focused on qualitative environmental assessment of products: EcoDesign Pilot, Information/Inspiration and Ecofaire. The authors thought this choice was relevant as the eco-design task had to be achieved in a very limited time. Moreover, the overall objective of this research is to test the main available categories of eco-design tools with designers, eco-design guides belonging to one of the targeted categories. The fourth tool, SIMAPRO, is an LCA tool taken as a reference for the case.

It is another subject of interest for the authors to study how designers can succeed in using LCA tools in this context, although these are supposed to require a significant amount of implementing time and expertise.

In order to gain a better understanding of the whole framework, data were synthesized on a SADT flow chart on Fig. 2.

2.2 Role of Experts and Researcher

2.2.1 Who Are the Experts?

At first sight, participants are considered as experts in eco-design. In fact their experience in eco-design rank from a few months time to approximately 15 years. They are divided into two categories: engineers in industry or consultancy (25%) and researchers (75%).

Eder [9] defines seven levels of expertise. After examination of behaviours and communicative acts during the experiment, it can be assumed that three categories of expertise are represented among the participants: competent, proficient, and expert.

A total number of 23 participants joined the experiment. They were randomly dispatched into four groups working on quoted tools (referenced #i).

Table 1 Framework of case study

Who? What?	Experts	Researcher
Process	Perception of process (P) by experts	Evaluation of process (P) by researcher
Results	Perception of results (R) by experts	Evaluation of results (R) by researcher

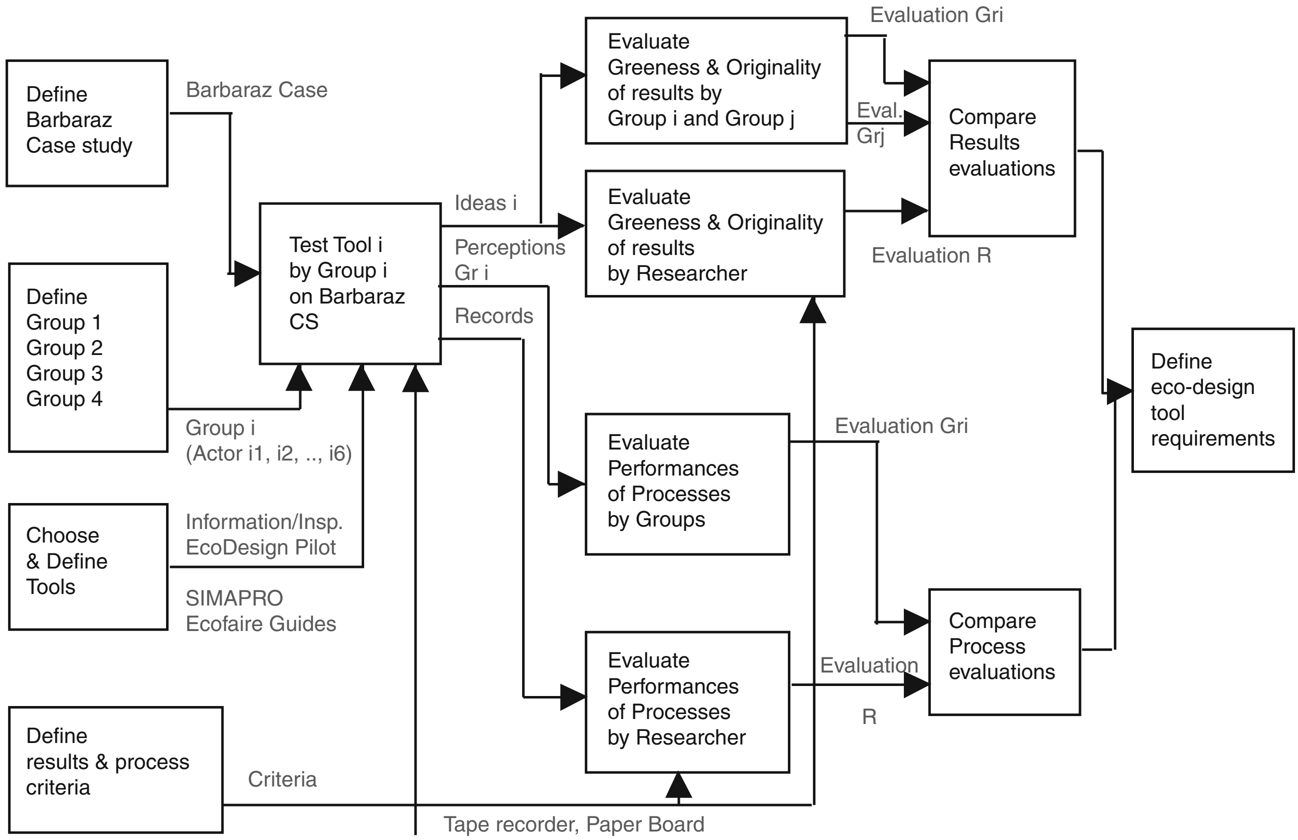

Fig. 2 Framework of the research method: SADT flow chart

Following the objective to cross judgements on process and results, participants were involved into three tasks:

1. Test a tool (group #i)
2. Give feedback on process Pi through a first e-mailed questionnaire (Q1)
3. Give feedback on one's group creative outcomes Ri AND on other groups' Rj through a second web questionnaire (Q2).

2.2.2 What Is the Role of the Researcher?

The researcher had two major tasks: animate one of the groups as a team-leader (Informa-tion/Inspiration) and evaluate, with appropriate independent criteria processes, the outcomes of the four groups.

2.2.3 Design Context

What type, or types of action operations are conducted during this case study? Participants are supposed to go through "critical situations of design process" mentioned by Eder [9], placing them in a context of non-routine operations.

Among the three categories, namely "Routine", "Risk" or "Safety and rational", the last one seems to be the most appropriate context within the four groups:

- Eco-design guides are not known by most participants, but team-leaders are familiar with those (apart from Ecofaire's team-leader).
- Topic of case study is novel to everybody.
- Participants are dispatched into groups with people they never collaborated with before.
- Moreover low expertise is needed on the product itself. Participants can easily rely on their personal experience and do not need to refer to external domain experts.

3 Requirements On A "Good" Eco-Design Tool

Requirements (abbreviated as Re) are dispatched into 4 balanced categories and 12 subcategories (Table 2). An effort was made to keep consistency on different levels. An indica-

Table 2 List of selected requirements on eco-design tools

Re	Expression	Indicators	References
Re1	A good tool favours learning of actors		
Re1a	Is easy to use and learn	Number of questions on tool	[4, 6]
Re1b	Favours interactions between actors	Number of constructive /destructive interactions	[10]
Re1a	Favours transformation of actors	Number of "coevolution" episodes	[3, 11, 12]
Re2	A good tool inspires confidence of actors		
Re2a	Helps understand rationale	Expression of function of tool (what it is for)	[4, 7]
Re2b	Gives a feeling of completeness (problem identification and solution finding)	Expression of completed work	[13]
Re2c	Generates reliable and rigorous results	Robustness of results	[4]
Re3	A good tool helps managing the complexity of problem		
Re3a	Limits quantity of required data	Number of queries on problem Time spent to gather data	[4, 6]
Re3b	Indicates lines of improvement	Expression of lines	[13]
R3c	Takes stakeholders into account	Numbers of quoted stakeholders	[3]
R4	A good tool helps with generation of relevant outcomes		
Re4a	Generates environmentally relevant outcomes	Perception of greenness	[4]
Re4b	Generates original outcomes	Perception of originality	[6, 10, 13]
Re4c	Helps representing outcomes	Level of detail in representation of outcomes	[9]

tion of experimental indicators associated with requirements and based on literature is given in the third column. All requirements with grey shadow on Table 2 will be addressed in this paper.

4 Empirical Work

It was decided to carry a participation action research. A vision on design brief as well as on planning of experiment is developed in this section.

4.1 Design Brief

Participants were asked to improve a disposable razor for man or woman (Fig. 3). Each group was provided the two sorts of razors with associated packaging (sachet or blister). Although being of medium complexity (but with several assembled parts), this product was expected to raise interest of participants due to the wide range of environmental issues to tackle.

Fig. 3 Disposable razors for men and women

4.2 Planning of Experiment

The actual experiment, named "Barbaraz case" took place over a one-day seminar and was planned in three stages (Fig. 4):

- Presentation by researcher of design brief and miscellaneous information on product (physiological, historical, marketing data on razors); presentation of eco-design tools.
- Test in groups during 1.5 h.
- First quick debriefing on outcomes of different groups.

4.3 Limitations of Experiment

Some limitations on this experiment have to be reported. This potentially affects the way ideas generated by groups were evaluated:

- Potential sensitivity to rating scale (1 to 5). More sensitivity could have been targeted with a wider scale, 1 to 10 for instance.

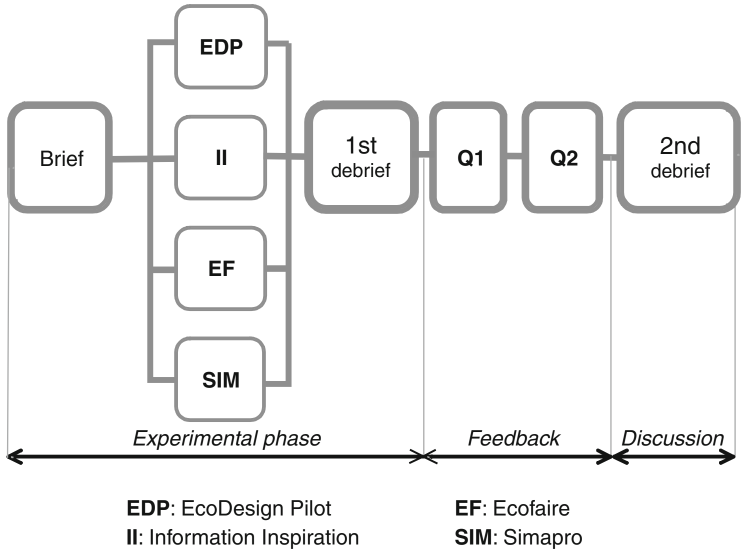

Fig. 4 Planning of experiment

- Lack of precision in the criteria used in questionnaires. The criteria were not previously collectively discussed by experts.
- Postponed evaluation of concepts several weeks after experiment.
- It was difficult to judge some concepts through the web questionnaire, especially those produced by other groups.
- The level of detail in the response questionnaires between the different groups was unequal. Notably none of the participants of Information/Inspiration gave feedback on ideas through Q2.
- Partial assessment of EcoDesign Pilot's ideas. Some ideas of this group could only be found on audio recordings. They were not integrated to second questionnaire on time.

5 Results

This section introduces the main results of the carried out experiment. It also summarizes the obtained outcomes with assessed eco-design tools.

5.1 Requirements Re4a and Re4b: Quality of Outcomes

According to different authors, a creative outcome is "an idea that is both original and appropriate" [14] Ideas presented in this paper will thus be assessed by experts against those two main criteria. It is noted that, in our case, appropriateness will be translated into "environ-mental friendliness". Three complementary criteria can be underlined (Yong et al. [15]):

- Fluency, i.e. number of ideas.
- Flexibility, i.e. span of generated ideas.
- Elaboration or level of detail of ideas.

Fluency, flexibility and elaboration will be examined on a second step of analysis (not presented on this paper).

5.1.1 Generated Ideas

Most generated ideas were either written down or sketched by participants; some ideas were just quoted. They all appear on Table 3.

5.1.2 Greenness and Originality of Outcomes

In this section "greenness" refers in a condensed way to environmental performance, or environmental friendliness of ideas. Ratings reported in this section are extracted from Q2 questionnaire (with a responding rate of 56%).

Inspired by Dorst [11], four scattergrams obtained for mean ratings of ideas against greenness and originality of ideas were plotted (Figs. 5, 6, 7, 8, and 9).

It can be observed that mean ratings all fit in [2.2;4.27] and [2.2;4.27] intervals as far as (respectively) originality and greenness are concerned. A focused scattergram of all ideas on Fig. 9 allows us to compare the spatial distribution of ideas in different cases. Four zones (A to D) can be defined

Table 3 Summary of ideas generated by the four groups. Ideas in italic were only orally quoted (and were not assessed through Q2)

Ecofaire	Information/Inspiration	EcoDesign Pilot	SIMAPRO
Recyclable monomaterial handle	*Recycled monomaterial handle*	Razor with nozzle	Short handle
Separable head	*Associate with organic cosmetic products*	Cleaning by manual pressure	Bamboo handle
Multi-purpose handle (toothbrush/razor)	*Blow out hair system*	Pushing out hairs	Three spare blades
Marking materials	*Shave in the "Ecoshower"*	Water-jet cleaning (on tap)	Sharpen blades
Biodegradable material	*Spherical handle*	*Spread blades*	Blades with two sides
Colours from vegetable pigments	*"Potato peeler" razor*	*Vibrating blades*	Wide and flexible blade
Cleaning hairs system	*Spatula with retracting blade*	*Indicate temperature (water) by change in colour*	Integrated foam applicator
Communication to consumers	*One handle for five heads*	*Indicate water consumption: change in stiffness of razor*	Solid foam
	Wire blade	*Indicate water consumption: bipper*	Scraper on handle
	Reloading of blades	*A gauging plug (water consumption, temperature)*	
	Interlocking heads		
	Soft protection blade		
	One blade		
	Lubricating reservoir in handle		

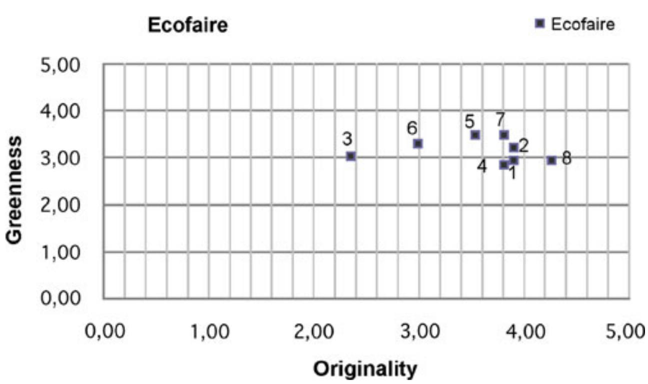

Fig. 5 Scattergram of ecofaire's ideas

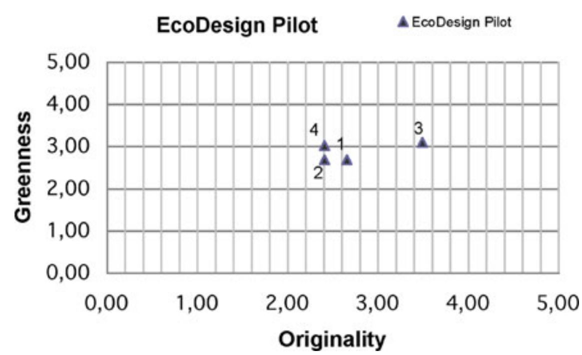

Fig. 7 Scattergram of ecodesign pilot's ideas

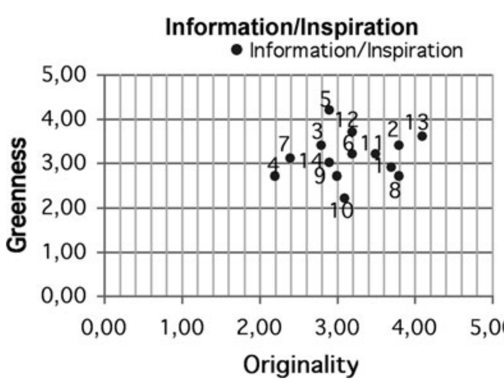

Fig. 6 Scattergram of information/inspiration's ideas

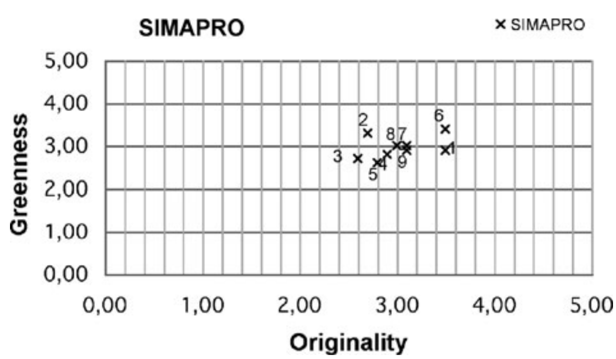

Fig. 8 Scattergram of simapro's ideas

thanks to global mean ratings of originality and greenness, respectively 3.13 and 3.02.

Considering Table 4, it can be calculated that most ideas with Ecofaire are seen as rather original (zones B and D), and with a consistent level of greenness. Ideas generated by Information/Inspiration are more numerous and cover a wider range in both originality and greenness. Nevertheless, 2/3 of ideas are situated in zones B and C. Less originality and greenness are seemingly inspired by EcoDesign Pilot's ideas. But it remains difficult to draw conclusions out of such a

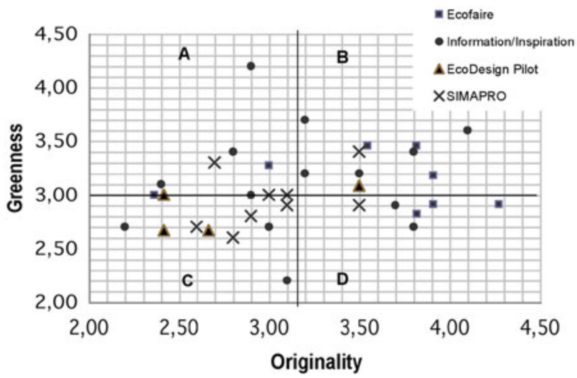

Fig. 9 Focused scattergram of ideas generated with four tools

Table 4 Percentage of assessed ideas in different zones

% ideas in...	EF	INF	EDP	SIM
Zone A	12.5	21.4	0	11.1
Zone B	37.5	35.7	0	11.1
Zone C	12.5	28.6	75	66.7
Zone D	37.5	14.3	25	11.1

reduced sample of ideas. As to SIMAPRO, main ideas were judged to be medium originality and greenness (zone C). Assumptions will be made to account for the various results in Sect. 6.

5.2 Requirements Re1a and Re3a: Usability of Eco-design Tools

Feedback data on usability of tested tools were extracted from Q1 questionnaire (with a response rate of 74%). Participants were expected to rate tools against usability criteria on a 5-point scale. They could also add comments on each topic.

Re1a is addressed through two questions: "Would you say this tool is easy to handle? Is it easy to understand?" and "What do you think of the setup time of this tool?" A score of 1 stands for "Very difficult to handle" or "Very long setup time". The associated question to Re3a is: "What is your impression on compatibility with few input data?" A score of "1" means "Poorly compatible".

Mean rating from experts on usability criteria are available on Fig. 10. These quantitative data are compared to what experts perceived and expressed through qualitative comments.

5.2.1 Easy to Handle

There is no significant difference between the average grades on this first criterion with the three guides, considered as very easy to handle. Nevertheless opinions about EcoDesign Pilot and Ecofaire are less radically positive. Translation of EcoDesign Pilot from German into French is criticized on several occasions. Respondents judge that Ecofaire is easy to handle with relevant available data, but also difficult to handle due to a confusing structure.

5.2.2 Time Efficiency

Ecofaire and EcoDesign Pilot are claimed, and assessed to be quick to set up despite a rather time-consuming preliminary phase where a lot of questions might be raised. Information/Inspiration is ambivalent. Although it scored highly, it could require a lot longer to set up should designers wish to go through all the resources. SIMAPRO is awarded a low score. Comments are helpful to understand that pre and post processing of data are responsible for low time efficiency.

5.2.3 Compatibility with Few Input Data

According to respondents all four tools seem compatible with few input data. This is also available for SIMAPRO as long as it is allowed to be used for rough assessment with low quality data. With a more conventional use it is of course necessary to gather a significant range of data, hence a low score on Fig. 10.

As a conclusion, the three eco-design guides lead to relatively homogenous perception and satisfaction from users according to usability. As expected, the only LCA tool, which greatly differs in its structure and results from others, shows much poorer usability features.

6 Discussion And Perspectives

6.1 Originality and Greenness of Outcomes

As far as originality is concerned, Information/Inspiration, which is dedicated to industrial designers, would be expected to be far ahead, but only ranks second. In fact it was first used late during the design session. This could account for the fact that propositions are not so innovative since they were, for most of them, generated without any specific guidance. Ecofaire provides the more balanced set of ideas with regard to originality and greenness possibly thanks to its qualitative and quantitative features. It is difficult to conclude about EcoDesign Pilot's assessed ideas. Some genuinely original ideas (such as a change in the stiffness of the razor) were not assessed by experts. A new assessment would be necessary in this case. Lastly, observation of SIMAPRO's group revealed a quick creative step followed by a long modelling and evaluating period. Ideas would therefore be expected to

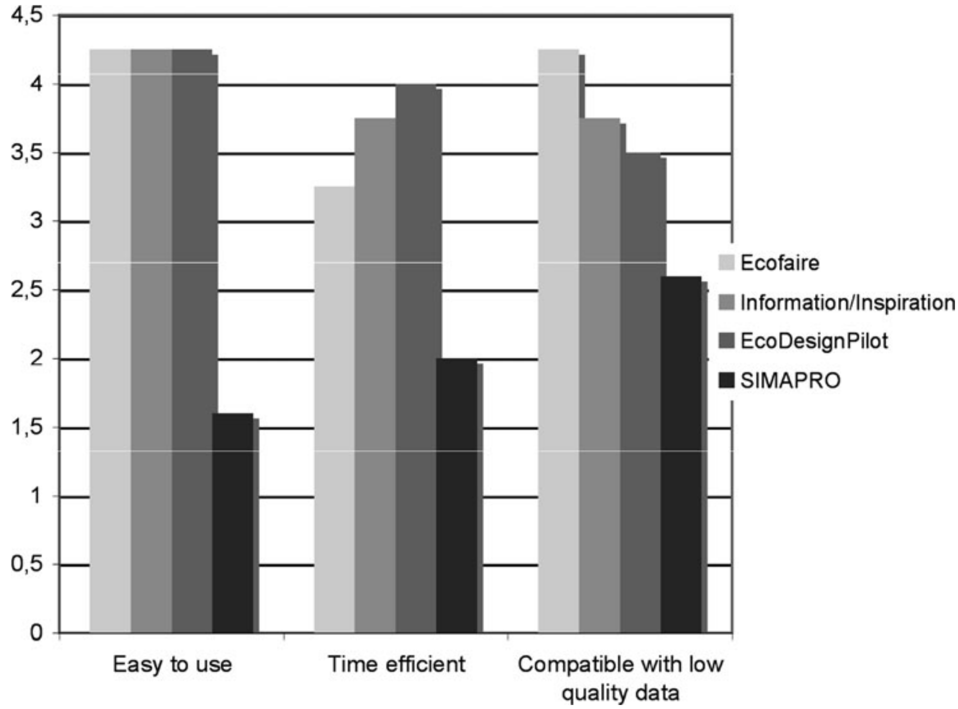

Fig. 10 Mean rating on usability of eco-design tools

be less original but more environmentally relevant than others. Surprisingly greenness of ideas is relatively low in this case.

6.2 Confidence in Results

Ecofaire and SIMAPRO inspire similar levels of confidence in results in both greenness and originality. A slightly higher rate is attributed to SIMAPRO, which is consistent with the nature of this tool. In our opinion, a quantitative assessment of ideas is expected to inspire a greater confidence in scientific users than qualitative assessment or even no assessment at all. In a previous experiment [10], strongly structured tools were supposed to favour consensus within groups. As it can be imagined that confidence and consensus are dependant, this might explain levels of confidence in Ecofaire and SIMAPRO (both rather structured tools). It can also be argued that confidence is probably a dynamic criterion supposed to evolve during project development. It would be interesting to visualize whether confidence in a given concept increases or decreases as time goes by.

6.3 Robustness of Method

According to Howard et al. [14] "With regard to assessing what is creative in a scientific case (. . .) there are few people who can make this judgment (. . .). Evaluation is done by applying subjective judgments". This can account for robustness of the part of our research method based on judgments of experts. As evidence of this, it should be added, for each evaluated idea, an indication of reliability between judges (known as inter-rater reliability). Moreover, reliability of each expert (or intra-rater reliability) should be justified. It is planned to compare scoring of an identical expert on a same concept appearing several times. For instance, cleaning hairs out of razor, one of the common concepts among three groups (with two available versions) could exemplify this reliability.

6.4 Proposition of a Model of Eco-design Process

The purpose of this paragraph is to give a first insight on a model of eco-design process matching our requirements list (cf. Sect. 3). Different relevant flows illustrate the use of eco-design tools by designers.

On model (a) (Fig. 11), basic flows of data are attached to the eco-design activity. Miscellaneous data on product (forming an ill-defined complex problem) are transformed into meaningful environmental data (ie a well-defined problem) and ideas of improvement (ie solutions). Model (a) is then enriched into model (b) (Fig. 11) by adding cognitive and social flows. "Ignorance" of actors is transformed into "Knowledge", and "Doubt" into "Confidence".

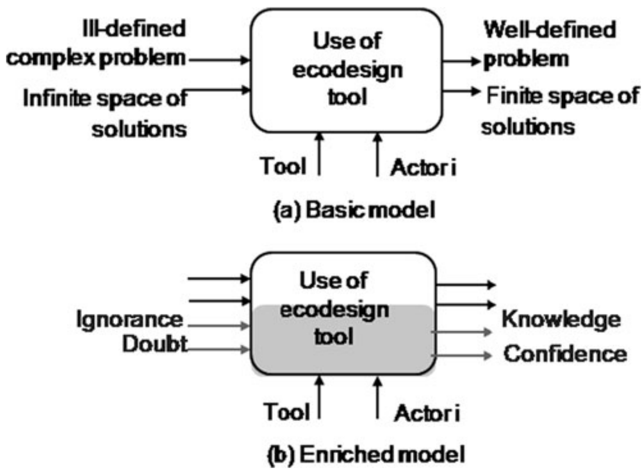

Fig. 11 SADT models (level A-0) of eco-design process

In future work, this model will be developed on level A0. An attempt will be made to clarify individual behaviours of designers from collective behaviours. Reflective actions of designers will also be mentioned.

6.5 Further Works

Further research on remaining requirements has to be carried out in order to characterize tested tools. A demanding work of transcribing and coding of all sessions is being performed to fulfil this purpose. Influence of expertise of actors using tools is an important factor to integrate. On a wider scope the first ambition of this contribution is to improve eco-design tools in a context-related way, depending on users and context of use. Yet it appears that the adopted methodology could match others types of methods in various fields. It is no doubt that a deeper understanding of how methods and tools are really used should give us valuable keys to develop new kinds of performances in companies.

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ACLODS – A Holistic Framework for Environmentally Friendly Product Lifecycle Design

S. Kota and A. Chakrabarti

Abstract Design for Environment (DfE) is an approach to design where all the environmental impacts of a product are considered over the entire life cycle of a product. Most DfE tools are conceptual in nature, and there is little adoption of these in industry. This chapter discusses the development of a holistic framework that should help in both generation and evaluation of environmentally friendly product life cycle proposals. The overall approach is to investigate literature to analyse the existing guidelines, methods, tools and methodologies for environmentally friendly product design, in order to identify the requirements for a holistic framework for design to reduce the environmental impact of a product lifecycle proposal. An ideal framework to satisfy these requirements is proposed.

Keywords Life cycle design · Product development · Design for environment · Life cycle thinking

1 Introduction

Products make a substantial impact on environment. The ratio of product mass to waste mass directly or indirectly produced as a result of the product during its life cycle is about 1:20 [1]. These wastes are thrown into the environment in each stage of the product life cycle from raw material extraction to product retirement. The lifecycle principle, where the whole impact of a product across its life is to be examined (from “cradle to grave”) has been gaining importance in product development [2]. In product development, we need to consider environment as one of the major criteria along with performance, quality and cost. Environment is gaining importance as an evaluation criterion because of government regulations, competition and customers’ requirement.

A number of guidelines have been proposed for assisting designers in the choice of materials [3], processes, energy [4], end of life processes [5, 6] etc. These guidelines primarily aid the end of life processes: disassembly, reuse, and recycling. Later, the efforts became directed on product life cycle as the basis for thinking, addressing all stages of a product’s life cycle, from material to after-use. There are many collections of general guidelines like [7]. These, however, are unlikely to be directly useful in the day to day product development activities because these are very generic and abstract in nature. All the reported work is on particular lifecycle phases or for a particular design stage or for a particular criterion. But we in reality the decisions taken are considering multiple criteria throughout design for whole lifecycle of the product. There is a need of a holistic framework that can be applied through whole design process for both synthesis and analysis of product lifecycles for multiple criteria to be used by designers.

2 Objectives and Methodology

2.1 Objectives

The objectives of this chapter are to:

- Establish the general need and specific requirements for a holistic framework for environmentally friendly product lifecycle design.
- Propose a holistic framework for environmentally friendly product lifecycle design to satisfy these requirements.

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2.2 Methodology

In order to establish the general need for a holistic framework for environmentally friendly product lifecycle design, a detailed literature survey has been undertaken. In the survey, existing guidelines, frameworks, tools and methods for supporting environmentally friendly product lifecycle design (EFPLD) have been reviewed by analysing their salient features, advantages and disadvantages, with the aim of identifying specific requirements for a holistic framework for environmentally friendly product lifecycle design (see Sect. 3). In addition, the outcomes from the series of design experiments have been analysed to understand the above requirements in detail (see Sect. 4). Based on the results of these, the dimensions of a holistic framework for product lifecycle design is proposed (see Sect. 5). The current frameworks and approaches are mapped on the proposed framework in order to identify areas where further work is needed before such a framework could be implemented for supporting environmentally benign product life cycle development (see Sect. 6).

3 Literature Review

There are two major types of tools available: analysis tools which are useful in finding the areas where the impact is substantial and where the existing product is weak, and synthesis tools which are useful in supporting development of solutions with reduced environmental impacts by helping a designer to generate appropriate alternatives.

The major barriers against environmentally oriented product development as listed by [8] are: low knowledge of the environmental impacts of specific products, low priority of environmental goals in product design, cost orientation, and lack of methods for early planning.

For assessment of environmental impacts of a product in a specific phase of its life cycle, it is prerequisite that details of all the specific processes that are present in that life cycle phase are available. The use of ecodesign tools may lead not only to environmental improvements but also towards options for cost reduction and new innovative directions [9].

Harsch in [10] proposed a tool called Life Cycle Simulation (LCS) which considers the lifecycle phases of material, production, use, after-use, and considers Performance, Cost and Environment as criteria for evaluation.

Kortman et al. [11] developed Environmental tool box which consists of task clarification, general design and detail design as design stages, analysis and improvement as activities, material, production, use and after-use as lifecycle phases, and performance, cost, manufacturability, safety, styling and environment as product criteria.

Hernández and Hernández [12] presented a tool Total Computer Aided Engineering (TCAE) which supports analysis in detailed design stages for material, production, use and after-use phases, considering performance, cost and environment as criteria for analyses.

Nissen [13] proposed The ideal-eco-product approach which deals with generating, evaluating and selecting objectives and solutions, for material, production, transport, use and after-use phases, in terms of environmental impact, cost and functionality as evaluation criteria.

Senthil et al. [14] developed Life Cycle Environmental Cost Analysis (LCECA) which supports sensitivity analysis of products or parts for material, production and after-use phases, in terms of environmental impact and cost criteria.

Anderl and Weißmantel [15] proposed a methodology called Design for Environment for the early stages of design, considering environmental impact in material, production, use and after-use phases, for analysis and improvement in terms of geometry, material and weight as criteria.

Roche et al. [16] proposed PAL framework which consists of requirements design, function design, general design and detail design as design stages, and analysis, synthesis and evaluation as activities, for material, production, use and after-use phases, based on environmental impact and structure complexity as criteria.

Spath et al. [17] developed two tools called REKON and LICCOS using which parts, assemblies and products can be developed during idea and conceptual design stage, considering material, production, use and disposal phases for environmental impact and cost criteria.

Wimmer [18] developed Ecodesign Checklist Method (ECM) that supports generation and analysis of both part- and product-level requirements for functionality and environmental impact as criteria, for the whole product lifecycle.

McAloone and Evans [19] presented the need and proposed the DEsign for Environment Decision Support (DEEDS) which is meant to support identification and evaluation of problems and requirements associated with material, production, use and after-use phases for all design stages.

Grüner and Birkhofer [20] presented a methodology called Integrated Product and Process Development (IPPD) for analysis and synthesis of parts and products with respect to material, production, use, recycling and disposal phases, considering functionality and environmental impact as criteria for trade-off during all design stages.

Reinhold et al. [21] developed a tool called Total Product Life-Cycle Cost Optimisation (TOPROCO) for analysis of parts, relationships and products using environmental impact cost and other costs during the after-use phase as criteria, in all stages of design.

Gómez et al. [4] developed a framework called Design for Energy Efficiency (EFEnEf) which deals with analysis, synthesis, evaluation and implementation of energy related environmental impacts, costs, quality and technical issues, in material, manufacturing, distribution, use and disposal phases, for both requirements and solutions.

Suiran et al. [22] proposed a method called Life Cycle Optimisation Design which considers manufacturing, use and end of life phases for generation, evaluation and selection of problems and solutions in all design stages, and insists on considering energy consumption, waste disposal, cost, functionality and quality as criteria.

Otto et al. [23] developed a tool to integrate CAD models with LCA which is used for analysis and improvement of parts, assemblies and products in material, manufacture, use and after-use phases with respect to environmental impact as criterion, and can be used in the detailed design stage.

Lindahl [24] developed a tool called Environmental Effect Analysis (EEA) which is useful in task clarification and conceptual design stages for evaluation, selection and follow up activities on parts and products, from the point of view of functionality and environmental impact criteria applicable during procurement, production, use and after-use phases of the product lifecycle.

Faneye and Anderl [25] proposed a tool called Life Cycle Process Knowledge which considers features, parts, assemblies and products for pre-manufacture, manufacture, use, recycle and disposal phases of their life cycle.

Park and Seo [26] developed a computer aided tool called Knowledge-based approximate life cycle assessment system (KALCS) which is used in embodiment and detailed design stages for evaluation and improvement of design solutions in material, production and use phases from the points of view of performance, cost, recyclability, environmental impact and efficiency.

Kurukawa and Kiriyama [27] proposed a framework called Green Life Cycle Model for generation of solutions for parts and assemblies in conceptual, embodiment and detail design stages with respect to manufacturing, use, disposal and recycle phases considering cost and manufacturability as criteria.

Pascale et al. [28] developed a tool called Ecobilan Group's Environmental Information & Management Explorer (EIME) for parts, assemblies and their relationships in task clarification and detailed design stages for generation and evaluation of requirements and solutions with respect to environmental impacts in manufacturing, distribution, use and end of life phases as criteria.

Takata et al. [29] developed a tool called Facility life cycle management for evaluation of parts, assemblies, relationships and features with respect to cost and strength analyses in embodiment and detailed design stages for the use and after-use phases of the product lifecycle.

Rebitzer and Hunkeler [30] proposed a methodology called Life Cycle Costing (LCC) for evaluation of solutions with respect to cost and environmental impact in material, manufacture, use and end of life phases.

Ernzer and Bey [31] presented a framework called Life Cycle Design (LCD) for analysis and synthesis of parts, assemblies, products and plant systems in various design stages for the whole lifecycle with respect to quality, technology, environmental impact and time as criteria.

Dewulf and Duflou [32] developed a system called EcoDesign Knowledge System which is useful for understanding environmental impact-related requirements for parts, assemblies, materials and functions, associated with material, manufacture, use and end of life phases, and for developing these during various design stages.

Maxwell and vanderVorst [33] proposed a method for Sustainable Product and/or Service Development (SPSD) which is used for analysis and synthesis of functions and solutions in task clarification and conceptual design stages from the points of view of functionality, environment, economy, social aspects, quality, market demand, customer requirements, technical feasibility, and compliance with legislation, during the material, production, distribution, consumption and end of life phases of the life cycle.

Nielsen and Wenzel [34] proposed a Procedure based on quantitative LCA for generation, evaluation, selection and update of requirements and solutions in abstract and detailed design stages, considering environmental effects, functionality and cost related to the various lifecycle phases as criteria.

Curran and Schenck [35] presented a Framework for Responsible Environmental Decision Making (FRED) for evaluation of solutions in the various lifecycle phases with respect to environmental impacts, price and performance as evaluation criteria.

One can summarise the following from analyses of the above guidelines, methods, tools, methodologies and frameworks. It is found that the following six dimensions are variously present in the approaches reviewed above:

- *Activities*: There are various activities envisaged to be carried out during each stage of design. Each approach is meant to support one, some or all of these activities.
- *Criteria*: There are various criteria which a product must satisfy. Each existing approach addressed only one or few of these.
- *Lifecycle Phases:* There are various life cycle phases of a product that need to be considered; each approach is designed to support one, few or all of these.

- *Outcomes*: There are various outcomes during a design process that should be supported. Each existing approach applies to only some of these.
- *Design Stages:* Each approach is applicable to one, some or all of the design stages.
- *Product Structure:* There are various aspects to the structure of a product, only some of which are variously addressed by the existing approaches.

The following preliminary sets of specific elements in each of the above six dimensions of the holistic framework are identified:

Activities: generate, evaluate, modify and select.
Criteria: performance, cost, environment, safety, styling, structure, quality, energy consumption, waste disposal, recyclability, efficiency, manufacturability, strength, time, social aspects, market demand, customer requirements, technical feasibility, compliance with legislation, and price.
Lifecycle Phases: material, production, distribution, usage and after-usage.
Outcomes: requirements and solutions.
Design Stages: task clarification, conceptual design, embodiment design and detail design.
Product Structure: product, assembly, relationship, part and feature.

4 Design Exercises

In the last section, the preliminary sets of dimensions for the holistic framework have been identified. In this section, analysis of the design exercises are done from the point of view of these six dimensions in order to modify and add further detail to the dimensions of the framework and its elements.

Following is a summary of the design exercises conducted. Of the twenty four design exercises conducted involving 8 designers and 4 problems, all four problems have been solved by different designers using one of the three interventions – general design literature, Environmentally Friendly Design (EFD) literature, a detailed impact assessment software. Out of the twenty four exercises, the sixteen design exercises that used EFD literature and detailed impact assessment software as intervention have been analysed in order to check and consolidate the requirements identified through literature review for the holistic framework, as discussed below.

The recordings of the design exercises were analysed to identify the following:

- The activities performed by the designers;
- The criteria used in the evaluation of a product's lifecycle;
- The lifecycle phases;
- The outcomes of a design process;
- The design stages through which designers proceed in a design process;
- The structure of a product as it evolves through the design process;

The designers followed the "think aloud protocol" while designing, and the whole process was videotaped and transcribed for analysis. The videos and documentations from the design exercises were analysed using video protocol analysis. The transcribed protocol was analysed by coding each utterance using the categories identified from the literature review detailed in Sect. 3 as the initial basis, and modifying them according to their efficacy in categorising the events captured in the utterances.

Identify the activities performed by the designers during the design stages. The following activities are identified after analysing the exercises: understand, generate, evaluate, modify and select.
Find the criteria of the product lifecycle that need to be considered. The following criteria have been observed after analysing the exercises: functionality, cost, environmental impact, maintainability, efficiency, performance, safety, ergonomics, aesthetics, manufacturability, quality, portability, usability, weight, compactness.
Find the lifecycle phases. The following lifecycle phases are identified after analysing the exercises: material: *extraction, processing* and *delivery*, Production: *manufacturing, assembly* and *in-plant storage*, Distribution: *packaging, loading, transportation, unloading* and *interim storage*, Usage: *installation, use, maintenance* and *repair*, After-usage: *disassembly, collection, transportation, reuse/remanufacture/recycle* and *disposal*.
Find the outcomes in design. Two types of outcomes are identified: requirements and solutions.
Find the different stages which the designers undergo in the design process. The following stages were verified during the analysis of the exercises: task clarification, conceptual design, embodiment design and detailed design.
The structure of a product as it evolves through the design process. Analyses of the outcomes of the exercises resulted in the following product structure and constituents: assemblies: collection of assemblies, subassemblies, parts and relationships between them in that particular assembly; subassemblies: collection of parts and relationships between them in that particular subassembly; relations: connection between one or more features of one part and one or more features of another part; parts: smallest (not in size but in that it cannot be divided any further into other parts and relations) physical elements of product; features: different geometrical forms in a part.

5 Holistic Framework – A Proposal

It is not the product but its lifecycle which would determine the impact on the environment. There is a need to consider different aspects while developing product lifecycles that are environmentally benign.

5.1 Development of Holistic Framework for EFPLD: ACLODS

From literature we identified activities, criteria, lifecycle phases, outcomes, design stages and product structure dimensions and some of the elements of these. From design exercises these dimensions are consolidated and additional elements like *understand* in the activities dimension, *maintainability, safety, ergonomics, aesthetics, portability, usability, weight, compactness* in the criteria dimension, *manufacturing, assembly, storage, loading, unloading, installation* in the lifecycle dimension, details of the design stages dimension and *subassembly* in the product structure dimension are identified.

Ideally one should consider all the elements of the dimensions identified from literature and design exercises to develop environmentally friendly product lifecycles; a holistic framework should consider all the dimensions and their elements identified above. Figure 1 shows the ACLODS framework which is formed by arranging the first letters of the following dimensions found above: **A**ctivities, **C**riteria, **L**ifecycle phases, **O**utcome, **D**esign stages, **S**tructure.

5.2 Elements in the Dimensions of the Framework

- The activities carried out by the designers, i.e. understand, generate, evaluate, modify and select of requirements and solutions should reflect consideration of different issues.
- In a holistic framework, criteria such as functionality, cost, environmental impact, maintainability, efficiency,

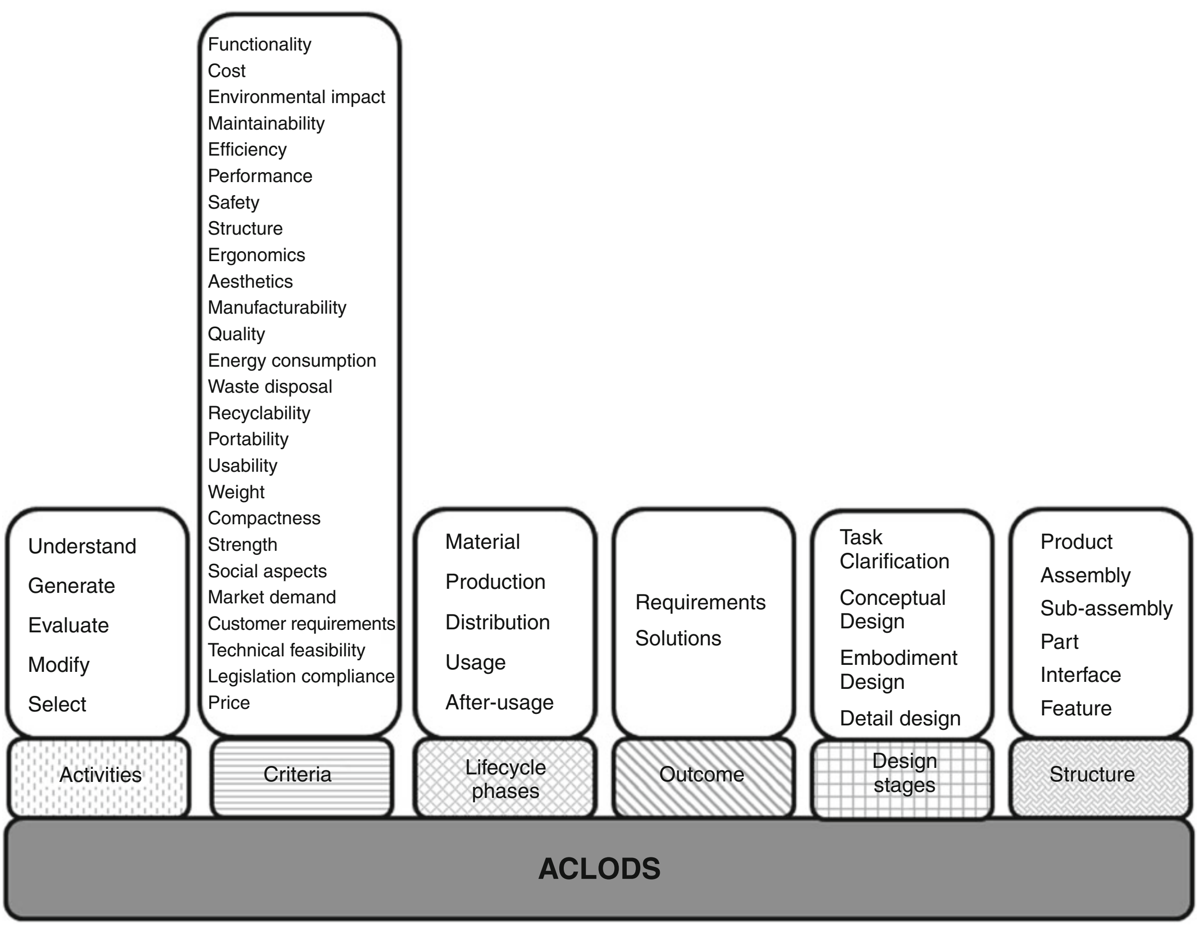

Fig. 1 ACLODS framework

performance, safety, structure, ergonomics, aesthetics, manufacturability, quality, energy consumption, waste disposal, recyclability, portability, usability, weight, compactness, strength, social aspects, market demand, customer requirements, technical feasibility, legislation compliance and price should be kept in mind through the design process. The list of criteria given here are comprehensive but not necessarily exhaustive; there may be other possible criteria that may have to be considered depending on the specifications and need.
- Designers should design the whole lifecycle of the product consisting of the following phases; material, production, distribution, usage, and after-usage. The material phase consists of extraction, processing, transport in material; the production phase consists of manufacturing and assembly; the distribution phase consists of packaging and transport; the usage phase consists of installation, use and maintenance; and the after-usage phase consists of collection, disassembly, and reuse or remanufacture or recycle or energy recovery or disposal of various portions of the product.
- During any stage of the design process, requirements or solutions should be understood, generated, evaluated, modified or selected (or rejected).
- The designers should take into account the criteria during every stage of the design process i.e., in the task clarification, conceptual design, embodiment design and detail design. When designers are engaged in working on requirements, they try to satisfy the requirements in terms of principles, layouts, sub-functions and final solution.
- Designers would work on product, assembly, subassembly, part, relationship and feature during any of the design stages.

6 Discussion

In this section, the approaches reviewed in Sect. 3 are mapped on to the proposed holistic framework, in order to see which areas are already covered by these existing approaches, and which areas are weakly supported and therefore should be improved.

The framework can be viewed in the following ways:

- Activities oriented view
- Criteria oriented view
- Lifecycle oriented view
- Outcome oriented view
- Design stage oriented view
- Structure oriented view

Figure 2 shows the percentage of approaches reviewed that consider the various dimensions of the framework. The approaches are categorised into three different sets a) those in which at-least one element in the dimension under focus is considered, b) those in which some of the elements in the dimension is considered, c) those in which all elements in the dimension is considered.

When at least one element is considered, it can be seen that the lifecycle dimension is considered most, which is not surprising given that literature search is focused primarily on design for environment. The second most considered is the criteria dimension and then the activity dimension. The next most frequently addressed dimension is the design stages, followed by structure; the outcome dimension is considered least frequently.

When some of the elements are considered, it can be seen that the lifecycle dimension is considered most, followed

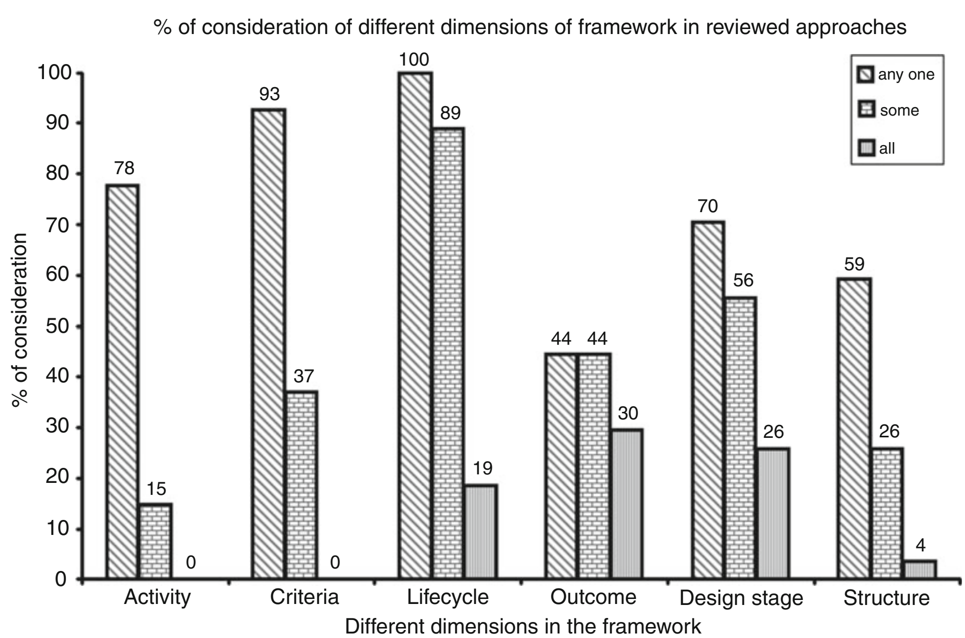

Fig. 2 Mapping of existing approaches with the ACLODS framework dimensions

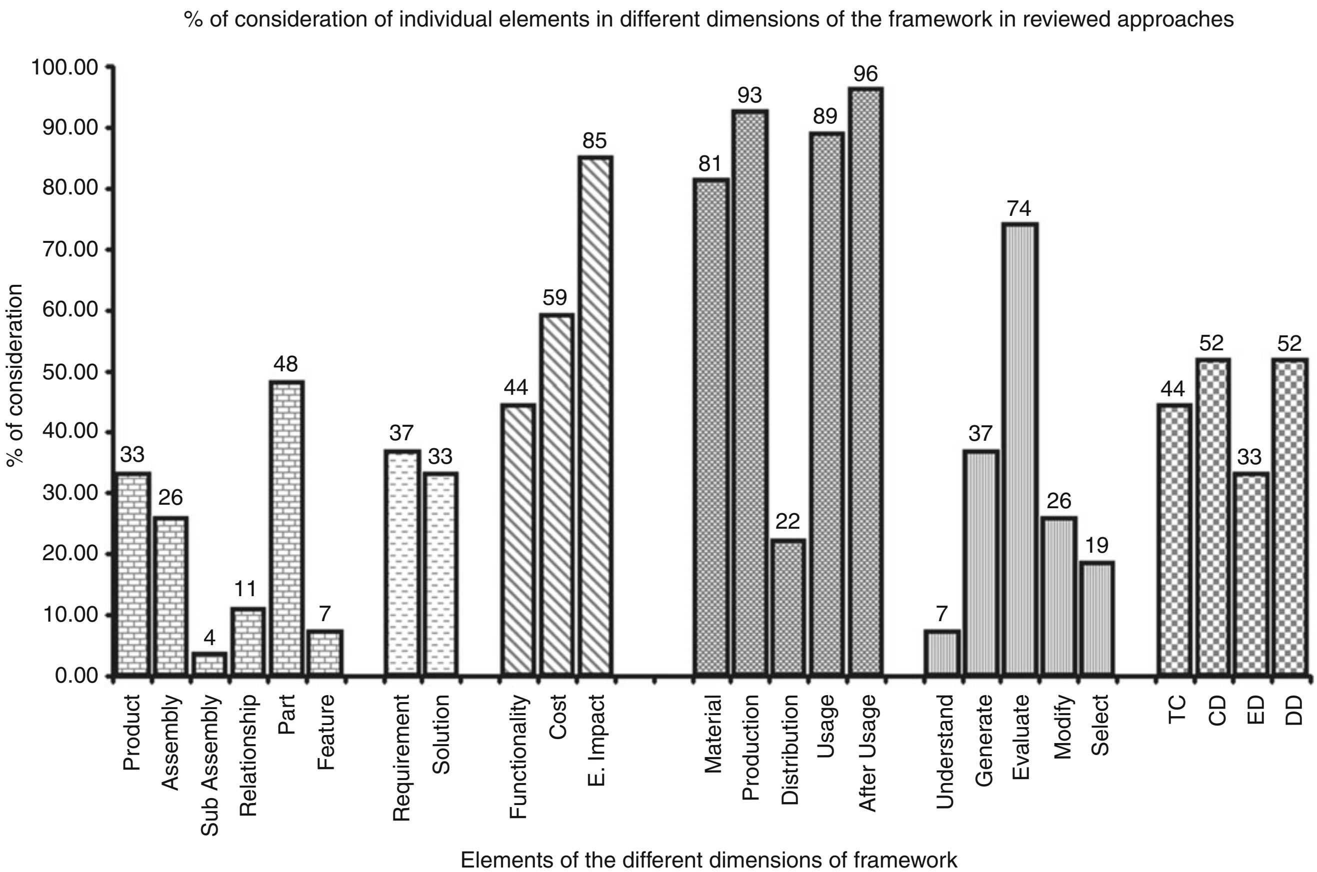

Fig. 3 Percentage of consideration of elements in the dimensions of the ACLODS framework in the approaches reviewed

by design stage dimension and then outcome dimension. The next most frequently addressed dimension is criteria, followed by structure and activity dimensions.

When all elements are considered, it can be seen that the outcome dimension is considered most, followed by design stage dimension, and then lifecycle dimension. The next most frequently addressed dimension is the structure. Activity and criteria dimensions are not addressed at all. As per the holistic framework, all elements in all dimensions should be considered; a relatively small proportion of these have been addressed by the reviewed approaches.

Figure 3 shows the percentage of consideration of different elements of each dimensions of the ACLODS framework in reviewed approaches. In the lifecycle dimension, after-usage, production and usage are considered by most of the approaches. In the criteria dimension, environmental impact, cost and functionality are the most frequently considered elements. In the activities dimension, evaluation and generation are considered most. In the design stage dimension, conceptual and detail design stages are considered most, followed by task clarification and embodiment design. In the structure dimension, part is the most frequently considered element, followed by product and assembly. In the outcome dimension, requirements and solutions are considered only in 30% of the approaches.

Table 1 first and second columns show the number of approaches among those reviewed where different dimensions have been simultaneously considered, where a dimension is taken to have been considered if at least any one element in that dimension is addressed (for example outcome dimension is taken as considered if requirement or solution or both are addressed). Table 1 first and third columns show the number of existing approaches in which different dimensions are simultaneously considered, where consideration of a dimension is taken to have happened if all the elements in that dimension are addressed (for example outcome dimension is taken as considered if requirement and solution both are addressed. Table 1 first and fourth columns show the number of approaches reviewed in which simultaneous consideration of different dimensions has taken place, where all the elements in all the dimensions are addressed. It can be seen fewer approaches address many elements in many dimensions. Figure 4 shows the percentage of occurrence of the same. From Table 1, we can see that only 3 (i.e. 11%, see Fig. 4) of the 27 approaches considered all the dimensions (but not necessarily all the elements), only 2 (i.e. 7%,

Table 1 Mapping of existing approaches on the ACLODS frame work

Combination of dimensions	No of approaches considering at least one element in at least one dimension	No of approaches considering all elements in at least one dimension	No of approaches considering all elements in all dimensions
ACLODS	3	2	0
ACLOD	3	3	0
ACLOS	7	4	0
ACLO	3	2	1
ACLD	4	1	0
ACLS	1	0	0
CLODS	1	1	0
LODS	1	1	0
CLOS	1	1	0
LS	1	0	0
LA	2	0	0

see Fig. 4) of the 27 approaches considered all the dimensions (with all the elements in one or more dimensions), and none (i.e. 0%, see Fig. 4) of the 27 approaches considered all the dimensions (with all the elements in all the dimensions). These are the only combinations we could found from the reviewed approaches.

Figure 4 shows the percentage of occurrence of the various combinations of dimensions of the ACLODS framework, as well as the various levels of comprehensiveness of the consideration of the elements in the dimensions within each combination. It can be noted that as the comprehensiveness increases, the coverage of elements in the dimensions become less comprehensive. There is only one approach that addressed all the elements the ACLO combination (Activities, Criteria, Lifecycle and Outcome). The elements of the design stages and product structure dimensions are not

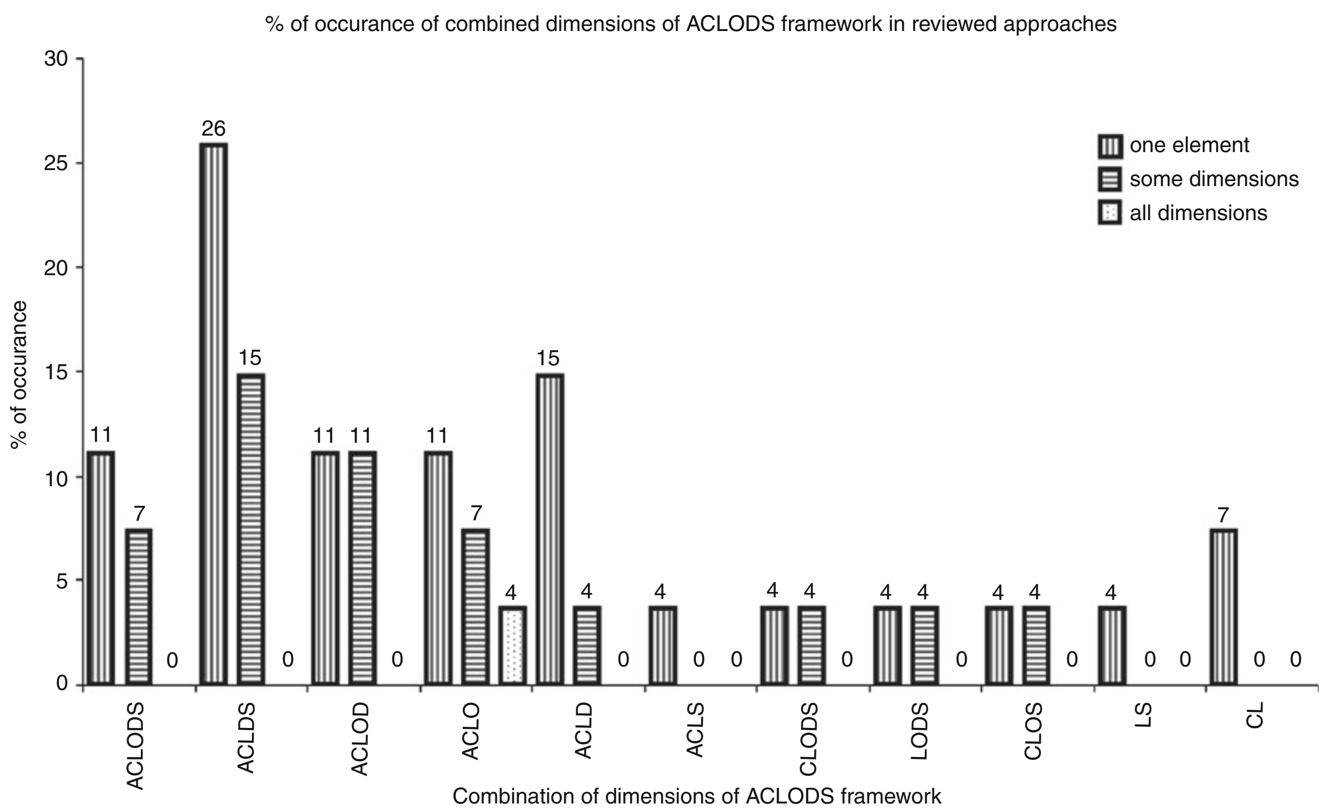

Fig. 4 Percentage of occurrence of combined dimensions of ACLODS framework in the existing approaches

addressed in full in any combination with other dimensions. In other words, none of the approaches apply to all design stages, and to all levels of granularity of a product's structure.

7 Conclusions

A detailed review of the current approaches helped in identifying the dimensions and elements that a holistic framework should constitute, and in establishing the areas in which the existing approaches are deficient.

A holistic framework should constitute the following six dimensions: (a) Activities, (b) Criteria, (c) Lifecycle phases, (d) Outcomes, (e) Design stages, and (f) Structure.

Analyses of design exercises has led to further consolidation of the elements of the dimensions of the holistic framework; from these, a holistic framework for environmentally friendly product lifecycle design, ACLODS has been proposed.

Existing approaches are mapped to the ACLODS framework in order to identify the areas which need improvement; this provided the directions for developing new approaches to fill the gaps and fulfil the overall need. The Design stage and the Product Structure dimensions are found to have been the least addressed in the approaches reviewed, and should be addressed in combination with the other dimensions. Our current research involves developing such a comprehensive design for environment platform.

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Models and Methods for Variation Management in Global Product Development

A New Approach to Transform a Constrained Geometric Object

M. Moinet, P. Serré, A. Rivière, and A. Clement

Abstract This chapter presents a geometric declarative model where objects and constraints are represented by a set of vectors in order to establish the specifications and to solve 2D and 3D problems. In this declarative model, vectors are not defined by their usual Cartesian coordinates but by their respective scalar products. Then a metric tensor characterizes the geometric object. To solve the problem, a new method based on the point displacement gives the final object satisfying all the specifications asked by the designer.

Keywords Geometric constraint · Non-Cartesian geometry · Tensorial model · Perturbation · Declarative modeling

1 Introduction

In this chapter, focus is made on the geometric modelers. Various types of geometric modelers can be found: parametric modelers which include B-REP (Boundary Representation), CSG (Constructive Solid Geometry) and hybrids. Variational modelers have a higher level of abstraction.

In these three types of approaches, every elementary object is defined by a set of parameters easily modified by the designer. As a result, the user can easily changes the generated object by simply modifying the value of a parameter defining the shape of a primitive and the system will automatically run the procedure to obtain the updated object. On the other hand, if the user wishes to modify a parameter not included in the construction tree or specify a constraint not accounted for the parametric model, the user will have to fully revise construction of the object. This may seem a trivial comment but it is nonetheless fundamental. In fact, during its life cycle, a digital mockup will be regularly modified by a multitude of different reasons. Most of the time, these modifications are extremely difficult to anticipate. Therefore, the digital mockup construction tree best able to support these modifications is impossible to determine beforehand.

Variational modelers provide a response to the above-mentioned disadvantage. In fact, in such modelers the elementary objects and related constraints are described rather than the objects creation procedure. This type of approach can be found today in modules of some 2D sketcher softwares [1] and/or for defining part assembly. The systems of geometric constraints to be solved are often very important in CAD, what obliges to decompose them. The decomposition methods reduce the systems of constraints to be solved into other sub-systems easier to solve. The found solutions will then be merged and will so supply all the solutions of the initial system.

There are two ways of decomposing a system of constraints according to the solving processing phase. These phases are described futher long. In the problem analysis phase, the structural decomposition methods help to reorganize the data of the problem to make its solution easier. These methods are also called directed graph methods because they use the properties of graph to identify the soluble sub-systems separately. They can be decomposed into two sub-methods: the structural methods such as downward approaches of Owen [2] and the ascending approaches of Hoffman, Lomonosov and Sitharam [3], of Fudos-Hoffman [4] and the rules-based methods. In the digital resolution phase, which occurs after the generation of the equations, the equational decomposition serves to decompose the system to be solved. This chapter will focus more on the resolution of the equations than on the reducing the complexity of the constraint system.

Here a variational model already presented by the authors [5] is used. In 2D, the geometric entities describing the object are the point and the straight line; in 3D, the point, the straight line, the plane, the cylinder and the sphere are used. Geometric constraints are added to these objects. These constraints may be of the following types: coincidence, orthogonality, parallelism, distance and angle. It will be described in the following section. The particularity of

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this model is that it is based on a vectorial representation of the geometric entities and the constraints. Third Section presents the adopted approach, that is to say, tensorial modelling that does not introduce any reference points. Section 4 gives details of the equation to be set up for the problem. Each type of specification imposed by the designer will be reflected in an algebraic equation determined from the metric tensor.

In relation to the work already accomplished by the team, this document presents a new method to generate the equations, based on the displacement of all the points of the geometry. The aim of resolution is then to find the transformation that enables the user to progress from initial geometry to final geometry respecting the specified constraints. This method is particularly appropriate for CAD as the user always starts by "drawing" an initial shape that is gradually modified to obtain the desired object.

Finally, Sect. 5 provides an iterative method enabling the system of equations to be gradually solved. The principle of this method is similar to that used by Newton-Raphson. One example is done at the end to illustrate. The conclusion is given in Sect. 6

2 Objects and Constraints

The geometric constraints are declared by the TTRS model (Technologically and Topologically Related Surfaces). This model was first used to describe the tolerancing of mechanical parts [6, 7]. It is based on the notion of surface invariance classes. There are seven surface invariance classes: any, prismatic, revolution, helical, cylindrical, plane and spherical. Each class is defined by its invariance degree and corresponding rotation and translation movement. For each TTRS invariance class, we define Minimum Reference Geometric Elements (MRGEs), themselves forming a TTRS of the same invariance class but only consisting of three elements – point, straight line or plane.

Thus thirteen relative positioning constraints can be expressed between two MRGEs. They enable the relative positioning of all the combinations of two classes between one another to be defined (See Fig. 1).

The constraints are of three types: distance (distance between two points, ...), angle (angle between two straight lines, ...) and coincidence (coincidence between two points, ...).

3 Tensorial Modeling

In most geometric models defined by constraints, the characteristic points of the object are represented in a Cartesian frame and the coordinates of these points are the unknowns of the system of algebraic equations to be solved. It is known that an incorrect choice of Cartesian frame may involve equation system configuration problems and give rise to resolution problems [8–10].

	MRGE straight line D_1	MRGE Plane P_1	MRGE point O_1
MRGE straight line D_2	C11: $D_1 = D_2$ **coincidence** *Cylindrical class* C12: $D_1 // D_2$ $D_1 \neq D_2$ **distance** *Prismatic class* C13: otherwise **angle and distance** *Any class*	C8: $D_2 \perp P_1$ **perpendicularity** *Revolution class* C9: $D_2 // P_1$ **distance** *Prismatic class* C10: otherwise **angle** *Any class*	C4: $O_1 \in D_2$ **coincidence** *Revolution class* C5: otherwise **distance** *Any class*
MRGE Plane P_2	sym	C6: $P_1 // P_2$ **coincidence** *Planar class* C7: otherwise **distance** *Prismatic class*	C3: **distance** *Revolution class*
MRGE point O_2	sym	sym	C1: $O_1 = O_2$ **coincidence** *Spherical class* C2: otherwise **distance** *Revolution class*

Fig. 1 13TTRS constraints with their invariance class

The model proposed is based on non-Cartesian modeling. Such methods exist like this one based on the determinant of Cayley-Menger but this method just involve the points and distance between these points [11]. The improved approach involves points, lines and circles in 2D and points, plans and spheres in 3D [12]. There are others way of representing the geometry. Indeed, new mathematical tools exist that form a unified framework that is Geometric Algebra based on Clifford Algebra. D. Hestenes sees that Geometric Algebra provides a language which, due it is geometric content, captures much of the logic that makes physics what it is [13–15]. Some scientists applied this technique like Timothy F. Havel on quantum mechanics in particular on the calculation of molecular conformation [16]. Others, like Hongbo Li have followed a Clifford algebraic approach in order to study hyperbolic Conformal Geometry [17, 18]. Nevertheless, Clifford algebra in CAD problems is not very studied for the moment.

The approach based on tensor uses a set of vectors describing the objects and constraints. A metric tensor from this set of vectors is constructed. This metric tensor fully defines the metrics of the object and does not depend on a particular Cartesian frame.

An added advantage of this approach is the possibility of ensuring specification consistency by verifying the mathematical properties of the metric tensor (symmetrical, semi-definite positive ...) For example, by calculating specific determinants, we can know whether the problem will have a solution.

3.1 Representation of the Geometry and Constraints

The geometric entities used are the point, straight line and plane – termed the MRGEs. Authors apply a related vectorial model to this data model. As a result:

- the point is represented by a point;
- the straight line by a vector and a point;
- the plane by a vector and a point.

Let us take an example, given $\mathbf{e_1}$ and $\mathbf{e_2}$ two elements in a vectorial space E. They are chosen as directional vectors of the straight lines running through points M and N.

Add a new unit vector to this space: $\mathbf{e_3}$.

Call l_3 the length between the two points M and N, thus giving: $\mathbf{u_{mn}} = l_3\, \mathbf{e_3}$.

The angle between the straight lines running through $\mathbf{e_1}$ and $\mathbf{e_2}$ will be written as α_{12} and can be obtained by the scalar product of these two unit vectors (Fig. 2).

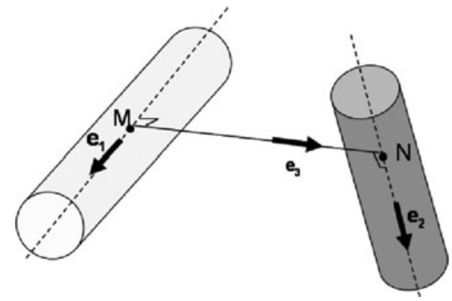

Fig. 2 Vectorization

3.2 The Geometric Model

3.2.1 A Few Reminders

Any vector $\mathbf{x}$ in a vectorial space with n dimensions in which a base $\mathbf{e_1}, \mathbf{e_2}, ..., \mathbf{e_n}$ is defined takes the form of:

$$\mathbf{x} = \sum_{i=1}^{n} \mathbf{e_i} x^i$$

Where $x^1, x^2, ..., x^n$ are the *contravariant* components of the vector. In another base $\mathbf{E_1}, \mathbf{E_2}, ..., \mathbf{E_n}$ it will have the coordinates $\mathbf{X^1}, \mathbf{X^2}, ..., \mathbf{X^n}$.

If the bases are linked by the relations

$$\mathrm{E_j} = \sum_{j=1}^{n} \mathbf{A}_\mathrm{j}^\mathrm{i} \mathbf{e_i}$$
$$\mathrm{e_i} = \sum_{i=1}^{n} \mathbf{B}_\mathrm{i}^\mathrm{j} \mathrm{E_j}$$

With the matrices $\mathbf{A}_\mathrm{j}^\mathrm{i}$ and $\mathbf{B}_\mathrm{i}^\mathrm{j}$ which are two inverse matrices:

$$\sum_{i=1}^{n} \mathbf{A}_j^i \mathbf{B}_i^k = \sum_{i=1}^{n} \mathbf{B}_k^i \mathbf{A}_i^j = \begin{cases} 1, \text{ if } k = j \\ 0, \text{if } k \neq j \end{cases}$$

Then the contravariant coordinates are transformed as

$$x^j = \sum_{j=1}^{n} \mathbf{A}_i^j X^i$$
$$X^i = \sum_{i=1}^{n} \mathbf{B}_j^i x^j$$

Authors will subsequently use the Einstein convention to simplify writing: if, in an expression, the same index is repeated at the top and bottom, the summation of this index is implicit (Fig. 3).

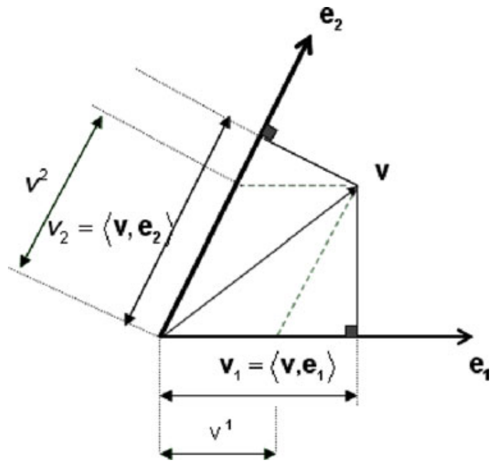

Fig. 3 2D representation of the covariant and contravariant components

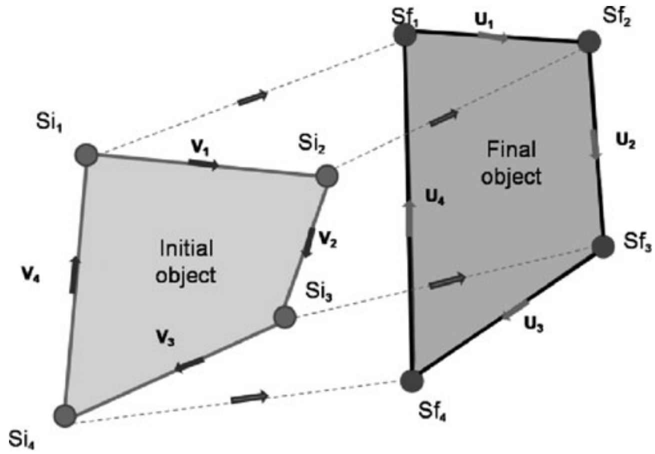

Fig. 4 Vertex displacement

In a Euclidean space, the scalar product of two vectors **x** and **y** is written as:

$$\langle \mathbf{x}, \mathbf{y} \rangle = \sum_{i=1}^{n} \sum_{j=1}^{n} \langle \mathbf{e_i}, \mathbf{e_j} \rangle \, x^i y^j$$

The metric tensor is defined as $\mathbf{G}_{ij} = \langle \mathbf{e_i} \, , \mathbf{e_j} \rangle = \mathbf{G}_{ji}$.

With the metric tensor, we can define the *covariant* coordinates of a vector.

$$x_i = \langle \mathbf{e_i}, \mathbf{x} \rangle = \langle \mathbf{e_i}, \mathbf{e_j} x^j \rangle = g_{ij} x^j$$

The contravariant components are obtained by means of an oblique projection of vector **v** on the vectors of the base $\{\mathbf{e_1}, \mathbf{e_2}\}$.

$$\mathbf{v} = v^1 \mathbf{e_1} + v^2 \mathbf{e_2}$$

The covariant components are obtained by orthogonal projections of vector **v** onto the vectors of the base $\{\mathbf{e_1}, \mathbf{e_2}\}$

$$v_1 = \langle \mathbf{v}, \ \mathbf{e_1} \rangle$$
$$v_2 = \langle \mathbf{v}, \ \mathbf{e_2} \rangle$$

3.2.2 Model Proposed

A geometric object is represented by a list of vectors. Given **V** a set of n non-normed vectors as $\mathbf{V} = (\mathbf{v_1}, \mathbf{v}_2 \, , \cdots , \mathbf{v}_n)$. Each vector is an oriented bipoint. For example, $\mathbf{v_1}$ has Si_1 as origin and Si_2 as target (see Fig. 4). The Gram matrix **G(V)** is defined by:

$$\mathbf{G}_{ij}(v) = \langle \mathbf{v_i}, \mathbf{v_j} \rangle$$

This matrix is also noted $\mathbf{G}_{\mathrm{ij}}$.

The two objects are represented by two different Gram matrices with the same size.

The variation $\mathbf{sf}_i - \mathbf{si_i}$ corresponds to the vertex displacement here $\mathbf{si_i}$ and $\mathbf{sf_i}$ are vectors which are the position of the vertex i before and after displacement.

An incidence matrix, **C**, makes the relation between each points of an object and vectors. It is an $n \times m$ matrix where n and m are the number of vectors and vertex respectively, such that $\mathbf{C}_{ij} = -1$ if the vector $\mathbf{v}_j$ leaves vertex $\mathrm{s_i}$, 1 if it enters vertex $\mathrm{s_i}$ and 0 otherwise.

Then, the edge relation for an initial object is:

$$\mathbf{v}_i = \mathbf{C}_{ij} \mathbf{si}_j \tag{1}$$

The edge relation for a final object is :

$$\mathbf{u}_i = \mathbf{C}_{ij} \mathbf{sf}_j \tag{2}$$

3.3 The Perturbation of the Initial Object Model

If **v** is a set of vectors of ranks r and **u** a set of vectors obtained after a transformation from an initial state to a final one, we are going to find the relation between these two states.

Note the vertex variation:

$$\mathbf{sf_i} - \mathbf{si_i} = \mathbf{\Omega_{ij}} \mathbf{v_j} \tag{3}$$

This matrix **Ω** is called the perturbation matrix from the initial state of the geometry to the final one. It is an $n \times m$ matrix.

Thanks to Eq. (3), the relation between initial vectors and final one is uncomplicated:

$$\begin{aligned} \boldsymbol{u}_{\mathbf{i}} &= \mathbf{C}_{ij}\left(\boldsymbol{\Omega}_{jk}\mathbf{v}_k + \mathbf{si}_j\right) \\ \mathbf{u}_{\mathbf{i}} &= \mathbf{v}_{\mathbf{i}} + \mathbf{C}_{ij}\boldsymbol{\Omega}_{jk}\mathbf{v}_{\mathbf{k}} \\ \mathbf{u}_{\mathbf{i}} &= \left(\delta_{ik} + \mathbf{C}_{ij}\boldsymbol{\Omega}_{jk}\right)\mathbf{v}_{\mathbf{k}} \end{aligned} \tag{4}$$

The purpose is to find a transformation of an object from its initial shape to its final one. **H** matrix characterizes the position of all geometry's points. Indeed,

$$\begin{aligned} \mathbf{H}_{ij} &= \langle \mathbf{u}_{\mathbf{i}}, \mathbf{u}_{\mathbf{j}} \rangle \\ \mathbf{H}_{ij} &= \left\langle \left(\delta_{ik} + \mathbf{C}_{ij}\boldsymbol{\Omega}_{jk}\right)\mathbf{v}_{\mathbf{k}}, \left(\delta_{jm} + \mathbf{C}_{jl}\boldsymbol{\Omega}_{lm}\right)\mathbf{v}_m \right\rangle \\ \mathbf{H}_{ij} &= \left(\delta_{ik} + \mathbf{C}_{ij}\boldsymbol{\Omega}_{jk}\right)\left(\delta_{jm} + \mathbf{C}_{jl}\boldsymbol{\Omega}_{lm}\right)\langle \mathrm{v_k}, \mathrm{v_m} \rangle \\ \mathbf{H}_{ij} &= \left(\delta_{ik} + \mathbf{C}_{ij}\boldsymbol{\Omega}_{jk}\right)\left(\delta_{jm} + \mathbf{C}_{jl}\boldsymbol{\Omega}_{lm}\right)\mathbf{G}_{km} \end{aligned}$$

This expression writes in the matrix form is:

$$\mathbf{H} = (\mathbf{I} + \mathbf{C}\boldsymbol{\Omega})\,\mathbf{G}^t\,(\mathbf{I} + \mathbf{C}\boldsymbol{\Omega}) \tag{5}$$

Note T the vectorial transformation $\mathbf{I} + \mathbf{C}\boldsymbol{\Omega}$. Thanks to the rank property:

$$rank\,(\mathbf{H}) \leq \min\left(rank\,(\mathbf{T})\,, rank\,(\mathbf{G})\right)$$

H will be a matrix of rank r.

Formula (5) above represents the variation of the geometric object. The elements of the perturbation matrix **Ω** are the unknowns of the problem.

4 Establishing the Equations of the Problem

The geometric constraints specified by the user lead to a set of equations. These equations can be classified into two types, depending on whether they come from length or angle.

Later in the document, element ij of matrix **G(V)** will be written as $\mathbf{G_{ij}}$(i.e. for the final matrix, noted $\mathbf{H_{ij}}$).

4.1 Length Equations

By definition, an element of matrix diagonal $\mathbf{G_{ii}}$ ($\mathbf{H_{ii}}$ for the final one) represents the squared length of an initial vector (final resp.). The length specification of the vector $\mathbf{v_i}$ imposed by the designer is denoted $\mathbf{s_{L_i}}$. Thus,

$$\sqrt{\mathbf{H}_{ii}} = \mathbf{s_{L_i}} \tag{6}$$

Given that each final tensor element is expressed as follows, according to the elements of perturbation matrix **Ω**:

$$\mathbf{H_{ij}} = \sum_{p=1}^{n}\sum_{q=1}^{n}\left(\delta_{\mathrm{ip}} + x_{ip}\right)\mathbf{G}_{\mathrm{pq}}\ \left(\delta_{\mathrm{qj}} + x_{jq}\right) \tag{7}$$

With $x_{ip}$the ipth element of the product matrix $\mathbf{C\Omega}$ and δ_{ip} the Kronecker symbol which equals 1 if i=p and, 0 otherwise.

By developing this last expression to the 1st order, we obtain:

$$\mathbf{H}_{\mathrm{ij}} \cong \mathbf{G}_{ij} + \sum_{p=1}^{n}\left(\mathrm{x_{ip}}\mathbf{G}_{\mathrm{pj}} + \mathbf{G}_{\mathrm{ip}}\mathrm{x_{jp}}\right) \tag{8}$$

In particular, for the elements of the diagonal:

$$\mathbf{H}_{\mathrm{ii}} \cong \mathbf{G}_{\mathrm{ii}} + 2\sum_{p=1}^{n}\mathbf{x}_{\mathrm{ip}}\mathbf{G}_{\mathrm{p}i} \tag{9}$$

And by developing Eq. (6), it becomes:

$$\frac{1}{\sqrt{\mathrm{G_{ii}}}}\sum_{p=1}^{\mathrm{n}}\left(\mathbf{x}_{\mathrm{ip}}\mathbf{G}_{\mathrm{pi}}\right) \cong \mathrm{s_{L_i}} - \sqrt{\mathbf{G}_{\mathrm{ii}}} \tag{10}$$

Terms $\mathrm{s_{L_i}}$, $\mathbf{G}_{\mathrm{pi}}$ and $\mathbf{G}_{\mathrm{ii}}$ are known. The unknowns of this equation are $\mathbf{x}_{\mathrm{ip}}$.

4.2 Angle Equations

By definition, an element $\mathbf{G}_{ij}$ of a Gram matrix represents the scalar product between vectors $\mathbf{v}_{\mathrm{i}}$ and $\mathbf{v}_{\mathrm{j}}$.

The designer requires the cosine of the angle between $\mathbf{v}_{\mathrm{i}}$ and $\mathbf{v}_{\mathrm{j}}$ to satisfy specification$\mathrm{S}\alpha_{\mathrm{ij}}$, resulting in the following equation:

$$\mathbf{H}_{\mathrm{ij}} = \sqrt{\mathbf{H}_{\mathrm{ii}}}\sqrt{\mathbf{H}_{\mathrm{jj}}}\ \mathrm{S}\alpha_{\mathrm{ij}} \tag{11}$$

Re-write Eq. (11) to move all the terms of ***H*** to the left of the equals sign gives

$$\mathbf{H}_{\mathrm{ij}}(\mathbf{H}_{\mathrm{ii}})^{-1/2}\left(\mathbf{H}_{\mathrm{jj}}\right)^{-1/2} = \mathrm{S}\alpha_{\mathrm{ij}}$$

By developing $\mathbf{H}_{\mathrm{ij}}$, $\mathbf{H}_{\mathrm{ii}}$ and $\mathbf{H}_{\mathrm{jj}}$ using Eq. (8) and by linearization to the 1st order, expression of a angular specification translates as follows:

$$\begin{aligned} &\sum_{p=1}^{n}\left(\mathbf{G}_{ip} - \tfrac{\mathbf{G}_{ij}}{\mathbf{G}_{jj}}\mathbf{G}_{pj}\right)\left(\sum_{k=1}^{m}\mathbf{C}_{jk}\boldsymbol{\Omega}_{kp}\right) + \left(\mathbf{G}_{pj} - \tfrac{\mathbf{G}_{ij}}{\mathbf{G}_{ii}}\mathbf{G}_{pi}\right)\left(\sum_{k=1}^{m}\mathbf{C}_{ik}\boldsymbol{\Omega}_{kp}\right) \\ &\quad\cong \sqrt{\mathbf{G}_{ii}}\sqrt{\mathbf{G}_{jj}}S\alpha_{ij} - \mathbf{G}_{ij} \end{aligned} \tag{12}$$

Terms $\mathbf{G}_{ip}$, $\mathbf{G}_{pj}$, $\mathbf{G}_{ii}$, $\mathbf{G}_{ij}$, $\mathbf{G}_{jj}$ and $S\alpha_{ij}$ are known. The unknowns are kpth elements of **Ω**.

5 Resolution

The system to be solved consists of non-linear relations (6) and (11). The known terms are the elements of the initial tensor **G**, the angle specifications $S\alpha_{ij}$ and the length specifications S_{L_i}.

To solve the problem, elements of the perturbation matrix $\boldsymbol{\Omega}_{ij}$ have to be found. Matrix $\boldsymbol{\Omega}$ defines the transformation of the set of vectors from the initial to the final state.

After qualitative analysis of the system to be solved:

- by counting the number of equations,
- by counting the number of unknowns,
- and also by qualitative analysis of certain angle specifications [19],

the resolution task can be called.

This analysis is not complete enough but the method proposed by D. Michelucci [20] appears applicable to this problem. This method called *the witness method*, allows finding the solution of a problem from a witness which itself is a solution of a variant of the system to be solved. The study of the witness can then replace that of the constraint system. Since the witness is a digital attribute of the system to be solved, it is easier to study. In CAD, the witness can be an attribute of the sketch given by the user. The probability digital approach was extended to the use of a witness by Michelucci et al.

The method most frequently used to solve this type of system, *(F(X)=0),* is that of Newton-Raphson. However, the algorithm implemented is a variation of the Newton-Raphson method and is presented in the next paragraph. Finally, this solution is illustrated by an example.

5.1 Description of the Method

The resolution method implemented is an iterative method, solving linearised Eqs. (6) and (11) step by step.

At each step, the linear system to be solved is generally under-constrained: only the equations corresponding to the specified terms of the final tensor come into play.

The system is written in the generic form $\mathbf{A}x$=b. An approximate solution can be searched. Use the least squares solution of the linear system $\mathbf{A}x$=b: the minimum norm solution of the system if it exists and, otherwise, solution x, minimizing the quadratic norm Min $\|\mathbf{A}x - b\|_2$of $\mathbf{A}x$–b.

The least squares solution of a linear system always exists and is unique. It is given by the classical formula:

$$x = \mathbf{A}^{\dagger}\mathrm{b} \qquad (13)$$

Where $\mathbf{A}^{\dagger}$ is the pseudo inverse of **A**.

In the prototype implemented under Matlab®, the pseudo-inverse of **A** is obtained by the function *pinv(**A**)*.

After solving the linear system, the perturbation matrix $\boldsymbol{\Omega}$ is reconstructed. The solution found by the solver is the one that minimize the matrix $\boldsymbol{\Omega}$*;* in fact it is the one that gets closer most geometrically to the initial solution.The solver gives only one solution. The scope is the CAD; the method which consists in giving us just a single solution is not annoying for the operators.

By applying Eq. (5), tensor G_{current} is calculated to be used as the input parameter for the following iteration.

Iteration is continued until the specifications are verified.

The algorithm can be represented in the form of the following diagram (Fig. 5):

5.2 3D Well-Constrained Example

To illustrate this method, one example in 3D is fully processed: a tetrahedron. Every step of the problem is successively described.

5.2.1 Problem's Description

This example is composed of 4 faces and 4 points, the irregular tetrahedron.

In order to obtain one geometry, the designer has to give a text file like Fig. 6.

Indeed, the designer builds it geometry step to step. First part; he describes all the elements of the geometry. First he gives all the vertex of the geometry; its number is indicated next to "VERTEX". Then keyword "Point"expected to enter a point's name like A, B, C in Fig. 6 and the coordinates of the point. Second, he gives the edge's list of all the edge of the object. This section begins by "EDGE" and after the keyword "Edge", the edge's name is done and the two points that composed it. Notice that the minus sign indicates that it is this point the origin of the edge. All the edge is oriented. Finally, the third part corresponds to the list of face "FACE". Every face is a triplet of three edges and the sign has got its importance.

Second part of this text file, are the specifications. For example, one angular specification is done and the designer has to specify the two sets. Then, he gives five length specifications, named l1 to l5 with the five values to respect.

This text file can be translated by this Fig. 7.

5.2.2 Vectorial Translation

The initial tetrahedron in the example used is defined by the tensor G_{init}. Thanks to the reading of the text file, it is easy

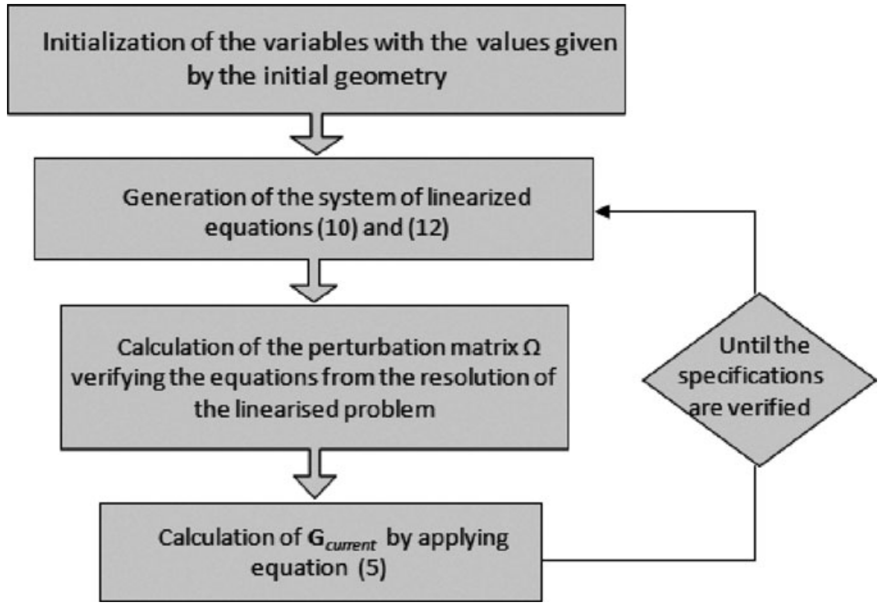

Fig. 5 Diagram of the implemented algorithm

```
#!VERTEX 4
Point: A (22.420713;39.068088;0.)
Point: B (96.527153;-28.075308;0.)
Point: C (-42.065776;-8.276318;0.)
Point: D (50.415214;10.09387;48.433486)

#!EDGE 6
Edge: AB (-A;B)
Edge: AC (-A;C)
Edge: AD (-A;D)
Edge: BC (-B;C)
Edge: BD (-B;D)
Edge: CD (-C;D)

#!FACE 4
Face: ABC (AB;BC;-AC)
Face: ADB (AD;-BD;-AB)
Face: ACD (AC;CD;-AD)
Face: BDC (BD;-CD;-BC)

#!ANGULAR SPECIFICATION 1
Angle: a1 (AB;AC) = 90°

#!LENGTH SPECIFICATION 5
Length: l1 (AB) = 100
Length: l2 (AC) = 85
Length: l3 (AD) = 65
Length: l4 (BD) = 75
Length: l5 (CD) = 110
```

Fig. 6 Text file proposed

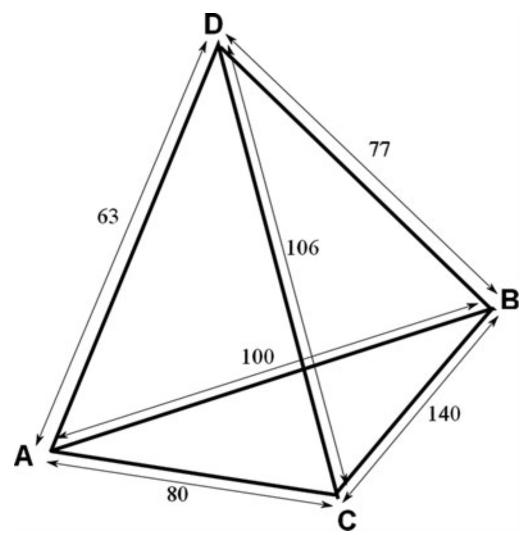

Fig. 7 Initial object – Example 1

to calculate the metric tensor corresponding to all the vectors of the geometry. This metric tensor is done by Fig. 8.

On this figure, *Gi* equals the *G* previously defined and the order of the vectors is as follows: *AB*, *AC*, *AD*, *BC*, *BD* and *CD*

The scenario to study is as follows: the user wishes to modify this initial geometry by imposing new dimensions to the bars and new angles. The length specifications are as follows:

AB is still equal to 100,
$AC = 85$ instead of 80,
$AD = 65$ instead of 63,
$BD = 75$ instead of 77,
$CD = 110$ instead of 106.

The angle specification is:
angle(AB,AC) = 90°instead of 101°

```
Gi    =

  1.0e+004 *

   1.0000   -0.1600    0.4020   -1.1600   -0.5980    0.5620
  -0.1600    0.6400   -0.0433    0.8000    0.1166   -0.6833
   0.4020   -0.0433    0.3969   -0.4454   -0.0051    0.4402
  -1.1600    0.8000   -0.4454    1.9600    0.7146   -1.2454
  -0.5980    0.1166   -0.0051    0.7146    0.5929   -0.1218
   0.5620   -0.6833    0.4402   -1.2454   -0.1218    1.1236
```

Fig. 8 The initial metric tensor associated to Example 1

5.2.3 Results Obtained

The prototype is developed in the Matlab® environment following the resolution principle developed in the previous section. The performance obtained is as follows:

- the system converges in 4 iterations in 0.05 s,
- the length and angle specifications are satisfied to within 10^{-11}.

The modified object is defined by the ***H*** *matrix*. The specifications given by the user (values in the box) are satisfied. The **H** rank is 3 and corresponds well to the dimension of the object sought (Fig. 9).

On this image, *Gn* equals the *H* previously defined and the order of the vectors is still as follows: *AB, AC, AD, BC, BD* and *CD.*

The results are added at the end of the text file (Fig. 10), in particular the three coordinates of each point (4 points in this example) for all iterations.

Figure 11 illustrates the geometry obtained:

```
#!OUTPUT 4
Itération.0
0.0000000000 ; 0.0000000000 ; 0.0000000000
100.0000003794 ; 0.0000000000 ; 0.0000000000
-15.9999992138 ; 78.3836722041 ; 0.0000000000
40.2000018640 ; 2.6753028028 ; 48.4334860000
Itération.1
0.0000000000 ; 0.0000000000 ; 0.0000000000
100.5865189720 ; 0.0000000000 ; -0.0000000000
-0.1842631157 ; 85.4867406890 ; -0.0000000000
42.8691982469 ; -3.3105289489 ; 48.9249766128
Itération.2
0.0000000000 ; 0.0000000000 ; 0.0000000000
100.0000457707 ; 0.0000000000 ; 0.0000000000
0.0011393387 ; 85.0001998382 ; 0.0000000000
42.9998249808 ; -3.8223876418 ; 48.5972357299
Itération.3
0.0000000000 ; 0.0000000000 ; 0.0000000000
100.0000000035 ; 0.0000000000 ; 0.0000000000
0.0000000061 ; 85.0000000191 ; 0.0000000000
43.0000000158 ; -3.8235293771 ; 48.5940390191
```

Fig. 10 Part added in the text file

```
Gn =

  1.0e+004 *

   1.0000    0.0000    0.4300   -1.0000   -0.5700    0.4300
   0.0000    0.7225   -0.0325    0.7225   -0.0325   -0.7550
   0.4300   -0.0325    0.4225   -0.4625   -0.0075    0.4550
  -1.0000    0.7225   -0.4625    1.7225    0.5375   -1.1850
  -0.5700   -0.0325   -0.0075    0.5375    0.5625    0.0250
   0.4300   -0.7550    0.4550   -1.1850    0.0250    1.2100
```

Fig. 9 The final metric tensor associated to Example 1

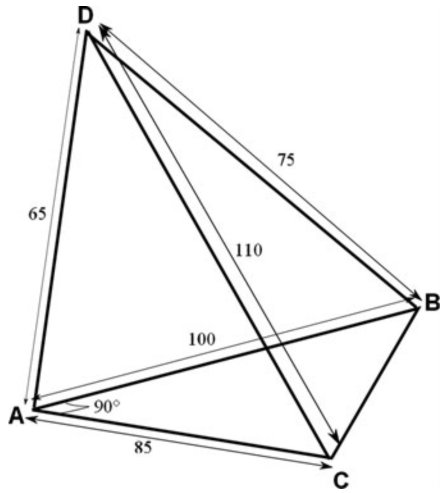

Fig. 11 Final object – Example 1

6 Conclusion

A vectorial representation is useful for characterizing objects and can be used to transform an object from an initial state to a final one.

We propose a new method based on point displacement to establish a final object capable of satisfying all the specifications required by the designer. In this chapter, an original method for generating equations and solving them is presented. It was validated by numeric experiments on the same prototype for 2D and 3D cases. The method successfully transforms the 2D and 3D geometry of an initial configuration into a final configuration. The modifications made to the geometry are of a dimensional type but it is likely that this method can be applied to objects defined by other types of constraints (chirality constraints for example).

In the future, the authors intend to use this approach to model and solve more complex problems with surface or volume type objects linked by constraints, ie angles and distances between planes, area of surface, etc.

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Design Method Taking into Account Geometric Variations Management Along the Design Process

R. Costadoat, L. Mathieu, and H. Falgarone

Abstract A highly effective product development is an essential prerequisite for the success of manufacturing enterprises. So, to produce mechanisms with guarantee of quality, delay and low cost, design has to take into account geometrical variations and to deal with it through Geometric Variations Management (GVM). The objective is to develop a method which studies GVM as the product evolves. The designer would be able to modify the technical solution without a total rebuilding of the tolerancing study. To do so, models of the parts are defined for each design stage, method and tolerance specifications are adapted to these representations. Graphical tools which have to deal with different types of data are developed in this method.

Keywords Design method · Geometrical variations · Tolerance specification and data sharing

1 Introduction

1.1 An Industrial Need

A growing issue in product design and concurrent engineering is the Geometric Variations Management (GVM). Customers demand forces industry to produce high-quality products with short delays and at low cost. Aeronautic companies are now industrial architects. Suppliers take part in the design process of their products. The fabrication, the assembly but also the design of their products are sub-contracted.

All the specifications that appears on Fig. 1 have to be understood by the industrial architect and the suppliers, to be as closer as possible from the requirements and to not have too fine restrictions which would lead to over-quality and expensive products. The specification of the product at each stage of its design is very important because the interfaces of each subassemblies are specified before the design of the geometry. It means that the specification must be adapted to a non finished product giving all the requirements needed to answer the consumer need. This chapter describes a method which takes into account specification tolerances since the beginning of the design process and leads to a complete tolerance specification of the parts.

1.2 Related Works

Some isolated studies and tools already worked in that way and are the base of this method:

- The Digital Mock-Up (DMU),
- The octopus and the FAST diagrams,
- The assembly graphs,
- The Small Displacements Torsor (SDT),
- The GeoSpelling model.

1.2.1 Digital Mock-Up

The Digital Mock-Up (DMU) can be defined as: "A computer-internal model for spatial and functional analysis of the structure of a product model, its assembly and parts respectively" [1]. The description of the product made by the DMU is available for its entire life-cycle. The DMU can be used to define the product along the use of the Geometric As Soon As Possible (GASAP) approach [2].

1.2.2 Octopus and FAST Diagrams

The octopus and FAST (Function Analysis System Technic) diagrams are used in Value Engineering and Analysis [3]. The method presented in this chapter starts just after the analysis of the customer need stage, the need is fully characterized. The next stage is the functional analysis of the

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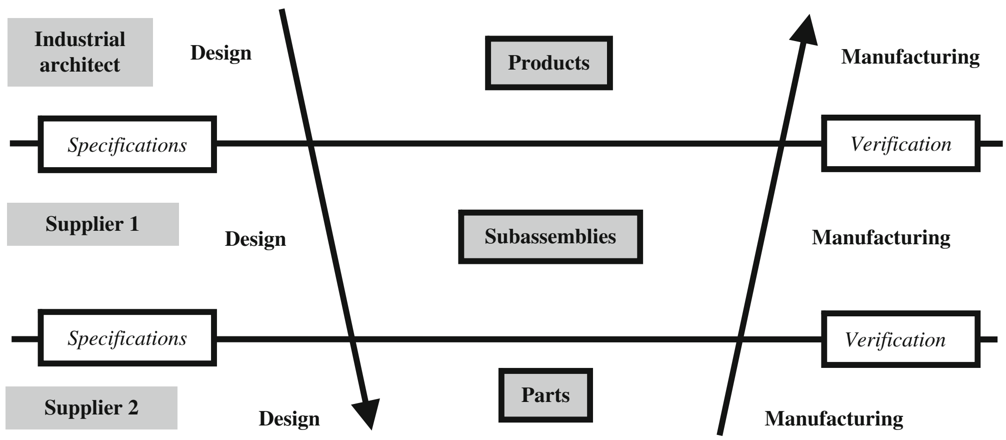

Fig. 1 Subcontract process

need, in order to determine the functional requirements. So, the first study is to analyse the connections of the product with the external environment. These connections are divided into two types of actions:

- Adaptation action of the product with an element of the surroundings: the product has to adapt itself to an element or the product acts on an element: Constraint Requirement (CR),
- Interaction of the product with elements of the surroundings: the product creates or modifies the relations between elements: Functional Requirement (FR).

The octopus diagram represents these actions. It is extracted from the APTE (APplication aux Techniques d'Entreprise) method. The identification of the possible actions, from an exhaustive inventory of the product's surrounding, is a powerful tool for the research of functional requirements. Other methods are able to generate these functions such as the research of existing products, the study of dissatisfaction of existing products, etc. The functional requirements extracted are then the inputs of the FAST diagram which allows the beginning of the functional analysis of the product. This diagram allows to represent for one solution, functions in a logical train answering the questions Why, How and When (to define simultaneity) [3].

1.2.3 Graphs

Each assembly or sub-assembly can be detailed with an assembly graph [2, 4]. In a graph, a vertex represents a part or an assembly, a continuous edge represents a Kinematic Link (KL) and a dotted edge represents a Geometric Requirement (GR). It allows to find risks of over-constraints described by cycles, and to find which parts are influent for some functions. A variant of the graph is the Assembly Oriented Graph (AOG). The orientation of the edge allows to define how parts are positioned to each others.

1.2.4 Small Displacement Torsor

The concept of the Small Displacement Torsor (SDT) has been developed in the seventies by P. Bourdet and A. Clément [5], in order to solve the general problem of the fit of a geometrical surface model to a set of points. In this context it is used to represent the geometric variations of the joints and the surfaces. Each component of the torsor is dedicated to a rotation or a translation displacement along a direction.

1.2.5 GeoSpelling Model

The GeoSpelling model, proposed by L. Mathieu and A. Ballu [6] and [7], accepted by ISO, is used to describe ideal and non-ideal geometry. Indeed, it allows to express the specification from the function to the verification with a common language. This model is based on geometrical operations which are applied not only to ideal features, defined by the geometrical modelers in a CAD system, but also to non-ideal features which represent a real part. These operations are themselves defined by constraints on the form and relative characteristics of the features.

All these tools are the starting point of this method but they have not been developed to fit fully the method, one of the purpose of this chapter will be to complete or modify their definitions to correspond to the expectations of the method.

1.3 *Current GVM*

The final geometrical result of the design process is a mechanism like the one presented at Fig. 2. This case study is a

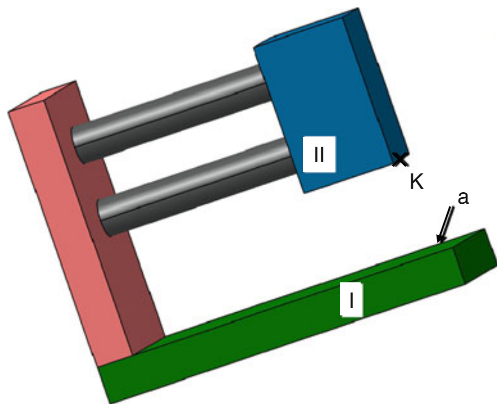

Fig. 2 CAD representation

prismatic pair, composed of two parallel axes. The two axes are in cylindrical pair. These links have internal gaps. The functional requirement under study is the deviation of the point K of the block II, with regard to the plane a of the bloc I during the translation.

Tolerance specification of parts has two important objectives and the purpose of the GVM is to guaranty at the end of the design process:

- the assemblability of the product
- the respect of the functional requirements

Usually, techniques for tolerance specification start at the detail design stage (Tolerance-Maps [8], CLIC [9]), on ideal functional surfaces and to generate relations between them to lead to a specification of the parts.

This way has advantages, indeed, at this stage of the design process, the geometry is fully defined so the ISO standards are well adapted. Also, all the intrinsic dimensions and characteristics needed are known.

But, there are some drawbacks to use a such method. Firstly, the product is finished so the GVM can not help the designer for the solutions choices which occurs during the design process. It is also illogical to do that way because it forces the design process to run backwards to extract the surfaces from the solid modelling, even when they were define earlier. Working at this stage avoid the extraction stage needed to select functional surfaces after the add of volumes. If the final product is modified after the tolerance specification, all the tolerancing study has to be rebuilt. And a final problem is that the subcontract of some parts of the mechanism is not allowed before the end of the design process, because the specification which gives the limits of the variations of the products is not yet established.

All these points show the interest of the development of a new way to develop the GVM totally connected to the design process.

1.4 Motivation of Development

The idea of this chapter is to start GVM early during the design process. Thus, it has to be introduced into the design process and all along the evolution of the product to the final solution. There are many motivations to do so:

- To use information, along the design process as it appears
- To facilitate collaborative engineering, share data easily within external enterprise
- To avoid starting over studies at each modification of the product or functions
- To manage specification uncertainties which appear during the design process

2 Interest of Tolerance Specification Along the Design Process

The purpose of the GVM is to generate a specification on the parts of the mechanism regarding to the requirements expressed by the customer.

As mentioned before, usually, the tolerancing work is done at the end of the design process because specification point out surfaces. The ISO standard forced designer to do so, because it is the most used specification language.

What are the interests to specify earlier?

- To be able to modify the technological solution without rebuilding studies
- To have products with a great variety of variants or modular products
- To valid technological solutions without modelling detailed parts

In the context of concurrent engineering, the system evolves from many sources simultaneously (aerodynamic, mechanic,...). That is why some modifications may occur at the last minut. The using of collaborative engineering forces to communicate modifications to the subcontractors in an univocal language to guarantee the quality of the product realised at this stage. These modifications force the designer to rebuild his tolerancing study from the beginning, to take into consideration the modifications. The idea of this new method is to start GVM before the choice of a technological solution. Thanks to that, if a modification is made on the product, the previous results are still valid from the point of view of variations.

Products are very similar in aeronautic from a model to another. It is a waste of time to restart the design of a new airplane from scratch. The solution would be to keep the common basis to start each study. The same idea can be used for modular systems, when modular products are identical but not assembled in the same way, the model of the modul must be reused for each assembly.

Which problems does it introduce?

This novelty involves some problems which have to be taken into account, indeed, there are two questions to answer:

- Q1: How to model the mechanism when the design is at the beginning?
- Q2: How to specify a product which is not defined by surfaces?

The Digital Mock-Up model makes it possible to realise the validation, from the variations point of view, of a design from the early conceptual design stage. But this description has to be validate to be used in the GVM. And if it is not sufficient, a work would have to be done to find a way to complete the lack of data.

It is the same thing with the FAST diagram, the tool is useful but it just allows the designer to express one solution. The need for this method is a mean to keep all the potential solutions proposed at each stage but not defined.

Also, constructive solutions which are the result of the FAST diagram are not yet really defined by standards. The use of this tool will force a total definition of its features. That is why additional functions must be added to the FAST diagram, to enrich it.

Some solutions have been found to solve these problems. For the question Q1, a first method [4] manages the granularity of structural information and decomposes the structural representation of the mechanism into three levels: product, sub-assemblies (parts level) and geometrical features level. A new approach [2] introduced new modelling stages: skeleton, skin and volumes.

For the question Q2, a new language of specification is needed because ISO standards can not specify other things than surfaces on isolated parts. The proposed approach is based on GeoSpelling. It is able to specify any geometric characteristic between ideal and non-ideal features as the angle between two straight lines for example. The tolerances specification is closer to the reality (actual product) and the uncertainties of specification are more controlled.

3 Tools for the GVM

As said before, the purpose of this chapter is to start GVM as soon as possible. Now the question is: When does the designer have enough data to work?

The GVM is based on the geometry and the structure of the mechanism (joints and requirements). As soon as the designer gets this data he can start working on the tolerancing.

The next section describes the design process of a mechanism, the idea is to figure out the moment when the data collected will be sufficient to start a first tolerancing study.

3.1 First Work

The first work done by the designer is the functional analysis. It is composed of three stages. The final stage proposes a constructive solution, so, it can be assumed that the moment when the GVM can start occurs during the functional analysis.

The functional analysis as shown at Fig. 3 purpose is to generate from a customer need a constructive solution like at Fig. 2.

The first stage of the functional analysis, called the Need Analysis, consists in the characterisation of the need. This stage will not be developed in this chapter because it has no impact on the GVM.

The second one is the Functional Analysis of the Need. The need is described by sentences, the first job of the designer is to translate the need into a language useful for the method. The purpose of this stage is to extract the Functional and Constraint Requirements of the product. These functions are all the properties that the mechanism must validate to answer the consumer need.

Functional and Constraint Requirements are outputs from the Functional Analysis and inputs in the Technical Functional Analysis. Their impact on the GVM is the same, in this chapter, only Functional Requirement will be treated.

The first tool linked to this stage the designer uses is the octopus diagram displayed on Fig. 4. It allows the designer

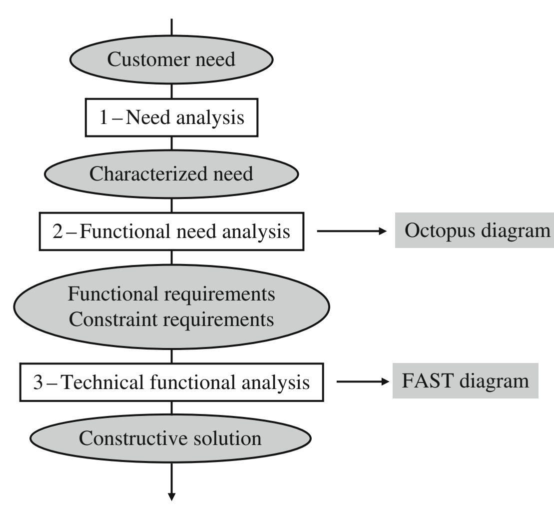

Fig. 3 Functional analysis process

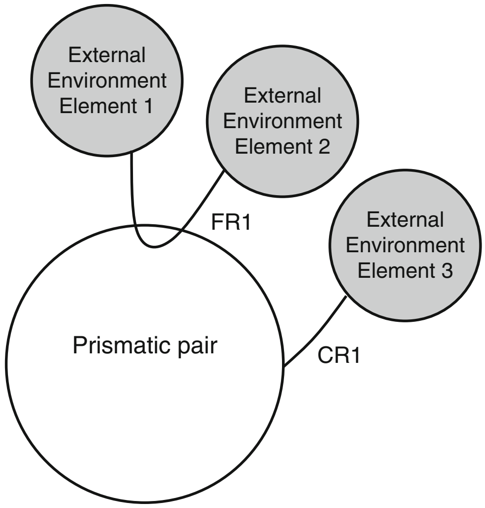

Fig. 4 The octopus diagram

to find the link between the product and the surrounding features.

The result of this stage is a list of functional requirements which have to be realised to satisfy the customer. For example, the functional requirement of the slide joint is to guide in translation the two elements of the external environment.

The third stage, called the Technical Functional Analysis, provides solutions to these functional requirements. The first solutions may not be linked to a geometry, but the first solution useful for the GVM is the one which introduces the first geometry and structure (joints, requirements, . . .). This particular solution indicates the starting point of the GVM.

The mechanism design, as said in the previous section, evolves following two ways. A structural way models the mechanism, with a view from product to parts level through sub-assemblies. A modelling way, represents the mechanism as a skeleton, then a skin and finally volumes.1 These steps are defined in the Geometry As Soon As Possible (GASAP) approach [2].

A skeleton is only composed by points, infinite straight lines and planes, a skin adds surfaces to the model and volumes model includes volumetric parts. The volume stage is not treated here, because the chapter approach is to specify early.

Product level can cohabit with sub-assemblies level and parts level, because their geometric behaviour is the same. The skeleton and the skin are tightly linked, indeed, the skin is directly generated around the skeleton. But their behaviour are different, that is why their studies are separated and why they use different models and tools.

That is why the following Technical Functional Analysis, will be later divided into two models, the skeleton and the skin.

For each model, this chapter will present:

- inputs
- tools
- outputs

It is very important to define what are the differences between the two corresponding design stages to mark very clearly their limits. Each stage corresponds to a level of definition of the model of the product, and allows some studies.

3.2 Technical Functional Analysis

The next tool used to deal with functional requirements is the FAST diagram, its purpose is to collect solutions which answers the question "How to realise this functional requirement?". The FAST diagram is build from left to right. It is a succession of technical functions which leads to a constructive solution.

To answer a functional requirement, many solutions can be found, the idea of this tool is to collect all of them and to choose the best one, from all points of view, to keep on designing. These solutions will be called "punctual solutions". The FAST diagram does not allows that method of approach. So a modification of some rules must be added to the existing FAST.

Rule 1: Punctual and constructive solutions are represented on the graph just after functional requirements (FR) or technical functions (TF), punctual are followed by technical functions, constructive by nothing. Constructive solutions are the final result of the FAST diagram. For one functional requirements or technical functions, as solutions as possible can be added but only one can be valid. Doing so, if the solutions which are not chosen are not represented, the FAST looks just like an usual one.

Rule 2: According to the standards [3] about the FAST diagram, the designer is allowed to put anything in the content of the constructive solution. With this method the solutions which are interesting for the GVM are the geometrical requirements on the assembly, the joints and the parts.

This graph will be called "FAST for solutions evaluation", it is displayed at Fig. 5.

3.2.1 The Skeleton

As said before, to be useful a punctual solution must contain geometry and structure, they are the inputs. The two definitions are very important, the first one describes the dimensional characteristics of the product, the second one

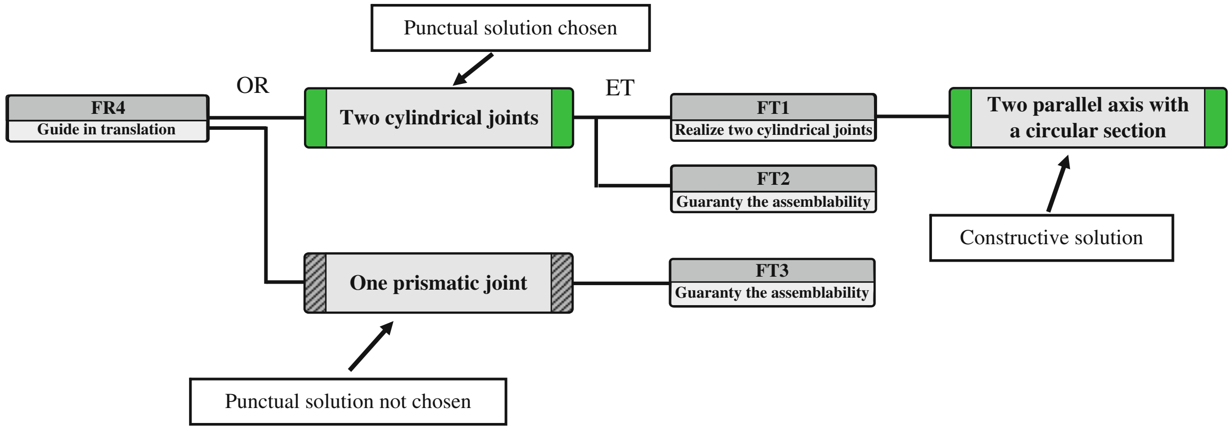

Fig. 5 Example of a FAST for solutions evaluation

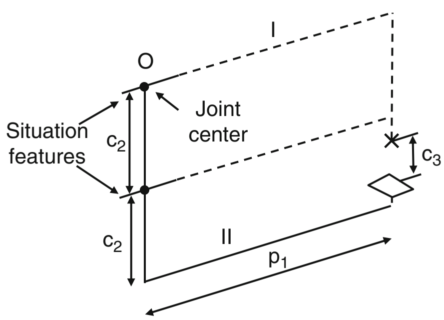

Fig. 6 CAD model of the skeleton

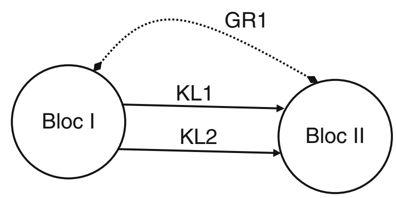

Fig. 7 The Assembly Oriented Graph

defines the kinematic and the function behaviour of the product. The tools are:

- The 3D CAD modeller
- The Assembly Oriented Graph
- The Small Displacement Torsors

They are presented in this chapter.

The geometry is represented on a 3D CAD modeller like Fig. 6, only by the skeleton model based on points straight lines and planes (TTRS theory) [10] (situation features). It allows to define the position and orientation of the joints and requirements. These situation features are linked each others by situation characteristics or parameters.

Each part involve in a joint has its own situation features which must correspond to the join behaviour, they are connected by constraints.

The structure of the solution is modelled by another graph called the assembly graph, like in Fig. 7. It is completed as the FAST evolves, each time a sub-assembly, a part or a requirement is created as a constructive solution, it is modelled on the assembly graph.

This graph is very useful to manage tolerances because it is a representation of the structure of the assembly. Each cycle containing parts and joints is a risk of over-constraint which provide the assembly of the mechanism, and each cycle including a requirement allows the designer to find which parts, assemblies and joints have influences on the requirements.

These two tools are very useful to describe the model, but they do not allow to simulate the behaviour of the mechanism. Since the beginning of the 80's and in particular with Requicha's works [11], many groups of research work on the subject while being based on various mathematical models. The mathematical tool used in that particular method for simulation is the SDT. The 6 components of the torsor represent the 6 displacements of a joint. Some are blocked by the joint, the displacements are then called Small Displacements, because they are limited at the geometrical variations of the parts involved in the joint. These small variations have an influence on the joint and consequently on all the mechanism.

The Small Displacement Torsor is represented as follows for the use case.

$$\{T_{I/II}\}_O = \left\{ \begin{matrix} \mathbf{R_{I/II}} \\ \mathbf{D_{I/II_O}} \end{matrix} \right\}_O = \left\{ \begin{matrix} \alpha_{I/II} & U_{I/II} \\ \beta_{I/II} & v_{I/II} \\ \gamma_{I/II} & w_{I/II} \end{matrix} \right\}_O \quad (1)$$

The formalism chosen is:

- capital letter = big displacement
- lowercase letter = small displacement

One other source of deviations is the parts geometrical variations. The skeleton only allows to model the variations between the nominal situation features and the real ones.

As said before, two types of specifications are generated:

- To guaranty of assemblability
- To respect of the functional requirements

The cycles corresponding to risks of over-constraints are modelled by equations of behaviour adding the SDT of the joints of the cycles and of the situation features. The resolution by a Gaussian elimination allows to find the degree of over-constraints and the components providing the assemblability.

The cycles connected to the requirements allows to generate inequations between the components of the SDT of the joints and situation features involved and the value of the requirement.

From the two types of mathematical equations and inequations, limits of the geometric variations are determined. The outputs is a local specifications on situation features of each block, like in Fig. 8.

Extracting the components related to a part, it is possible to manage local conditions of parts and to specify the parts individually, on the skeleton model.

The outputs at this stage of the GVM helps the designer:

- to modify a technical solution to remove over-constraint
- to reduce a dimension which make difficult the respect of a requirement
- to specify the behaviour of some joints in order to subcontract the manufacturing
- to specify a part individually

At the end of this stage, there is not enough data to carry on with the study. Indeed, all the interfaces are modelled by Small Displacement Torsors but to be closer to the reality, the real data which has an impact on the interfaces are the intrinsic dimensions of the surfaces involved in that joints. That is why, the model needs to be completed with the surfaces. The FAST diagram helps to choose surfaces according to the solutions chosen at the previous stage. These surfaces have to be coherent with the solution previously chosen. The next stage is called the skin of the mechanism.

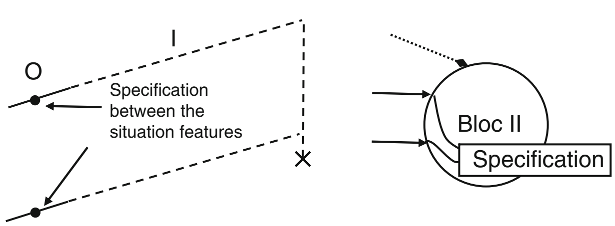

Fig. 8 Specification of an isolated part

3.2.2 The Skin

At the end of the previous stage, joints are represented by the situation features and the relations between each others. The variations of the joints are represented by values in some components in the Small Displacement Torsor.

The idea of this parts is to introduce new inputs which are the intrinsic dimensions (the diameter of a cylinder for example) of the mechanism which are the source of the joint behaviour. For example, the small radial displacement allowed in a cylindrical joint is due to the difference between the diameters of the shaft and the hole.

Tools are modified to be adapted to this new inputs, surfaces are added to the 3D CAD model, the Assembly Oriented Graph becomes the Contact Oriented Graph defined later.

On the skeleton this displacement was modelled by a SDT on the interface, here, thanks to the skin, it is possible to be closer to the reality and to directly specify intrinsic dimensions of the parts.

This evolution corresponds to a solution to make the system evolve in the FAST diagram. For example, there are many technical solutions to realise a cylindrical join, the designer can choose to insert a part with a cylindrical section or two spheres along an axis into a part with a cylindrical hole, like in Fig. 9. For a different geometry, the kinematic behaviour of the joint is exactly the same.

I a same way, a solution may be the using of additional parts to realise the joint (mechanical bearing, . . .).

The geometry evolves from the skeleton to the skin model adding all the functional surfaces of the parts, diplayed at Fig. 10.

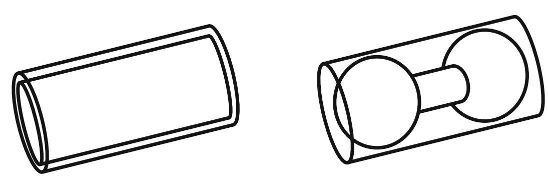

Fig. 9 Two solutions for a cylindrical join

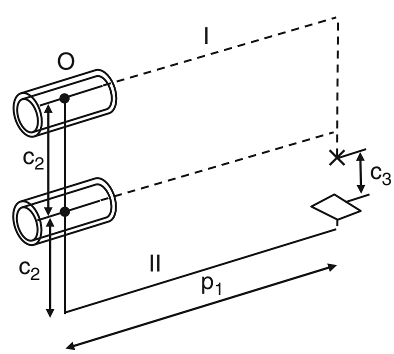

Fig. 10 Geometry with the skin model

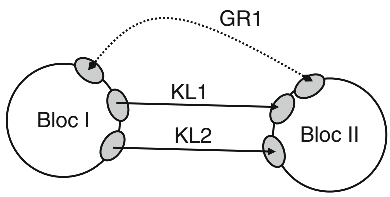

Fig. 11 The assembly graph with surfaces

The structural model evolves in two ways. First, the surfaces are graphically represented by poles at the interfaces between the parts and the joints, like in Fig. 11.

In a second way, joints are decomposed into elementary joints. For example, a complete joint can be realised by two perpendicular planes and an straight line, that generate over-constraints and to resolve it, designer has to choose the component blocked by surfaces from the most influent to the less.

Like in the previous stage, the outputs are mathematical equations and inequations which allows to specify the parts, but, this time, intrinsic dimensions are taken into account.

A repartition of the geometric variations which is not developed in this chapter allows to isolate the parts in each equations. These mathematical relations are local conditions between the functional surfaces of a part. They represent a mathematical expression of the specifications.

4 Conclusion and Perspectives

This chapter outlines a new approach: "tolerancing at the earliest". The GVM and the specification is taken into account as soon as possible. The idea is to ensure the continuous consistency between the specifications and the geometric model of the mechanism. Tolerancing is not treated at the end of the design process but earlier and at different stages, on the skeleton and on the skin.

The result is interesting because not only the specification of the parts is really close to the need, but also the technical solution is improved early in the design process by the GVM.

Thanks to the tools involved in the method, the data management is easier. These tools are connected to each other and that provides a solution which allows change management of the DMU. The GAIA software developed by EADS Innovation Works provides the data models presented in this chapter.

There are different ways to improve the method. Firstly, the GVM has not been developed yet to optimise the tolerances values. Introducing statistic models in the method will help in that way. The second is to study how to manage the contacts by discretizing parts. A way to determine the number and the position of those discretization points should result from a trade-off between an accurate discretization and a reasonable computation duration.

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Integration of Multiphysical Phenomena in Robust Design Methodology

D.S. Nguyen, F. Vignat, and D. Brissaud

Abstract Due to the development of science and technology the requirements of customers and users for a product are more and more tight and higher. The satisfaction of these, such as quality, reliability, robustness and cost of the product plays an important role in the context of global and concurrent economy. However, there are many variation sources during the product life cycle such as material defects, manufacturing imperfection, different use conditions of the product, etc. It can make the designed product not to meet fully the requirements of the users. Thus, we propose, in this chapter, several analysis methods based on data mining tools in order to analyze the result of performance simulation of the product taking into account the geometrical deviations generated during its life cycle. These methods allow classifying and identifying factors that influence on performance of the designed product. With these methods, the product designers can analyze the "real" performance under geometrical variation sources generated in the practical environment. Moreover, the proposed methods can be used to transfer back the result of the "real" performance analysis of the product to the manufacturer and product designer in order to obtain a robust product.

Keywords Product life cycle · Manufacturing simulation · Robust design

1 Introduction

Robustness of the performance of a product is a key factor in product design under uncertainty and variation sources during its life cycle, including material properties, manufacturing operations and practical environment. Actually, from designer's brain to users' hands, the product must pass through many stages of its life cycle (see Fig. 1). The variability generated in each stage, like geometrical deviations, obviously have an influence on the performances of the product. It can make the designed product not to meet fully the requirements of the customers and the users.

Each part making up the product is manufactured from raw material during the manufacturing stage, using the processes such as forging, cutting or grinding. The geometrical deviations on each part are generated and accumulated over the successive set-up of the manufacturing process because of the inherent imperfections of material, tooling and machining. Then, the parts with deviations are assembled at the assembly stage. The deviations of the surfaces of each part, generated at manufacturing stage, influence the assemblability and the final geometry of the product. The geometry of the product is, therefore, different from the nominal one at the end of these two production stages.

On the other hand, the current product modelling technology, based on the commercial CAD/CAM/CAE tools, is not capable of taking into account these deviations. Most of the simulations performed to predict the behaviour

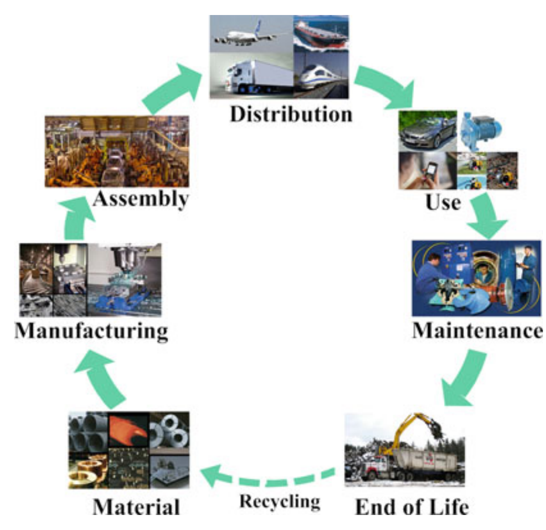

Fig. 1 Closed loop product life cycle

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and the performance of a product (kinematics, dynamics, aerodynamics...) are based on the nominal model of the product. Since the model cannot deal with the geometrical deviations generated throughout the whole product life cycle, the variation of product behaviour and performance cannot be caught. Thus the "real" performance of the product, which is different from the designed one (nominal performance), cannot be verified. The risk is then that the designed product does not meet fully the requirements of the customers and of the users. In that situation, the product-process design has to be considered as not good or at the least not robust.

In order to study the effect of geometric variability on product performance, there are important issues that have to be considered:

- How to model the geometrical deviations of a product generated in the successive stages its life cycle?
- How to simulate the "real" performance of the product that is of the product with geometrical deviations?
- How to identify the variation sources that affect on the performance of the product?

Some answers exist today in the academic research for each question. In order to find out a complete answer, it is necessary to develop a model of geometrical deviations of the product that has to be consistent with all the stages of the product life cycle. This model has to allow the integration of these deviations into the simulations of the product behaviour. The aim is to predict the "real" performances of the product taking into account this geometrical variability.

This chapter proposes several analysis methods based on data mining methods in order to classify and identify the variation sources that influence the performance of the product. The proposed method is used to analyze the result of performance simulation of the product based on a model of geometrical deviations and a method to predict the real performance of product [1, 2]. The aim is to adjust the designed product or the proposed manufacturing processes in order to obtain a robust design.

2 Literature Reviews

There exist some models to estimate the geometrical deviations of the part and the product generated by the manufacturing and assembly processes in the manufacturing and assembly stages of its life cycle. This variability can make the designed product not to be reliable and robust. Thus, there have been many researches on robust design for decades in order to minimize the effects of variability on product performance.

2.1 Manufacturing Stage

Several models of manufacturing defects to simulate the manufacturing process and identify error sources have been proposed. The classic studies to examine the variations of the dimensions of part produced by the manufacturing processes were mentioned in [3].

Zhou et al. [4] proposed a state space model to describe the dimensional variation propagation over multistage machining processes. Differential motion vector, a concept from the robotics field, is used in this model as the state vector to represent the geometrical deviation of the workpiece. This model provides a quantitative relationship between the fixture locator errors and the final workpiece geometrical error and has great potential to be applied to fault diagnosis and process design evaluation for complicated machining processes.

Villeneuve et al. [5] proposed a method to perform 3D manufacturing tolerancing for mechanical parts. The geometrical deviation model of the part, the part-holder and the machining operations of a set-up in the manufacturing process is based on the concept of small displacement torsor (SDT). The SDT concept, coming from metrology [6], has been used to model the variations due to the positioning of the workpieces during the successive set-ups of the manufacturing process as well as the machining operations. Vignat and Villeneuve [7] propose a model of manufactured parts (MMP), generated by simulation of the manufacturing process and that stores the 3D manufacturing defects. In this model, the defects generated by a machining process are considered to be the result of two independent phenomena: the positioning and the machining deviations accumulated over the successive set-ups. The positioning deviation is the deviation of the nominal part relative to the nominal machine. The positioning operation of the part on the part-holder is realized by a set of hierarchically organized elementary connections. The manufactured deviations of surface relative to its nominal position in MMP are expressed by the parameters of SDT.

2.2 Assembly Stage

A product is made up of a set of parts assembled following a specific process. Each part has to pass through the manufacturing stage where geometrical deviations are generated. Then the product has to pass through assembly stage. Assembly stage of the product life cycle is an essential stage of its life cycle, and it obviously brings its share of deviations to the product. Several models of dimensional variation propagation in the assembly stage have been proposed.

Ceglarek and Shi [8] proposed a model of dimensional variation applied to the sheet metal assembly. They apply their model to the automotive body assembly to make diagnosis and reduction of source of dimensional variability. Shiu et al. [9] proposed a model of multi-station assembly process in order to diagnose the automotive body dimensional faults. This model is based on the design information from the CAD system and allows a system behaviour determination based on the in-line measurements of the final product. The model is only applied to the automotive sheet metal assembly.

Mantripragada and Whitney [10] proposed a model for mechanical assembly using State Transition Model approach. All dimensional variations from successive assembly stations are accumulated into the final assembly station by the space vectors. However, this model for the mechanical assembly only simulates the assembly process of perfect parts. The geometrical deviations generated during manufacturing stage of each part are not taken into account in this model.

Huang et al. [11] proposed a Stream-of-Variation Model (SOVA) for 3D rigid assemblies' dimensional variation propagation analysis in multi-station processes. This model is also based on State Space Model approach. In comparison with the model presented by Mantripragada and Whitney [10] this model takes into account the deviation of the surfaces of the parts but does not link these deviations to any manufacturing process.

2.3 Robust Design

Geometrical variations of the product throughout its life cycle, especially manufacturing and assembly stage can make the designed product not meet fully the customers and users requirements. It is thus necessary to manage the causes and consequences of the geometrical variations at the design stage and reduce the impact of these variations on product performance in order to obtain a robust design.

The objective of robust design is to minimize the effects of variation or uncertainty of the source without elimination of these sources [12]. In other words, a robust design is insensitive to a variety of sources, including manufacturing imperfections, variations in material properties, and the operating environment. The fundamental principle in robust design is mentioned by Taguchi [13]. He summarized the quality loss function by the Eq. (1). The function means that any deviation from the target value leads to a quadratic loss in quality or customer satisfaction.

$$L = k(y - m)^2 \tag{1}$$

Where y represents the performance parameter of the system, m represents the target or the nominal value of y, L represents the quality loss and k is a constant.

Taguchi breaks the design process into three stages:

- System design – involves creating a working prototype
- Parameter design – involves experimenting to find which factors influence product performance most
- Tolerance design – involves setting tight tolerance limits for the critical factors and looser tolerance limits for less important factors.

Since many successful applications in engineering industry are being expanded to different fields. All the robust design study can be classified into two categories: the stochastic approaches and the deterministic approaches [14].

The stochastic approaches use probabilistic information of the design variables and the design parameters, such as their mean and variance, to analyze the system robustness. Parkinson [15] proposed to use engineering models to develop robust design in order to reduce the sensitivity of the design to variation. This method was used in tolerancing in order to solve the problem of determining optimum nominal dimensions of manufactured components and improving assembly quality without tightening tolerances. Chen et al. [16] classified the robust design into two general categories following (see Fig. 2):

Type I: minimizing variations in performance caused by variations in noise factors (uncontrollable parameters), such as ambient temperature, operating environment, or other natural phenomena, etc.

Type II: minimizing variations in performance caused by variations in control factors (design variables), such as material properties, manufacturing quality variations, etc.

They also developed a robust design procedure that integrates the response surface methodology with a compromise decision support problem in order to overcome the limitations of Taguchi's methods. This procedure includes three steps:

Step 1: Build response surface models to relate each response to all important control- and noise-factors using the Response Surface Methodology (RSM).

The response surface is established by the design of experiments method and fitting a response model. This model can be expressed by the Eq. (2):

$$\hat{y} = f(x, z) \tag{2}$$

Where $\hat{y}$ is the estimated response and x, z are control and noise variables.

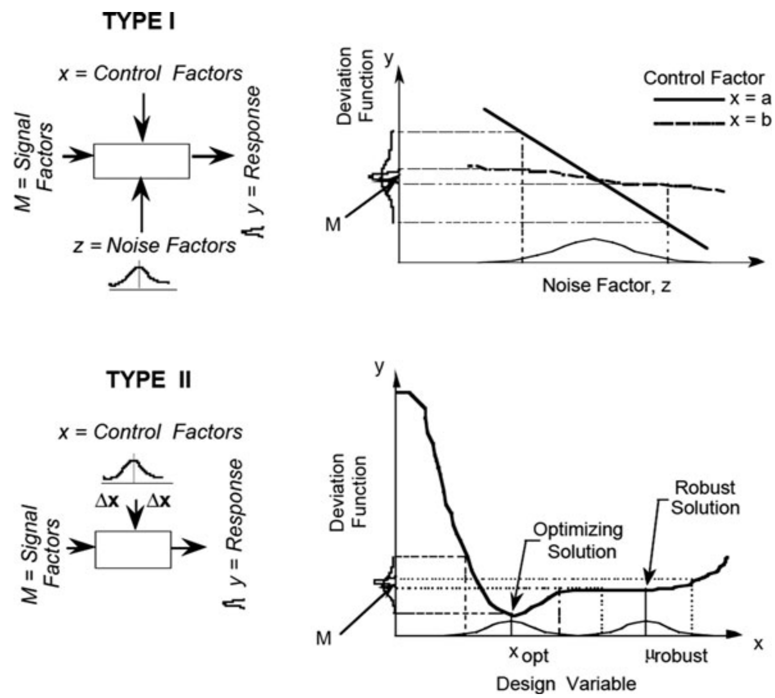


Fig. 2 A comparison of two types of robust design [16]

Step 2: Derive functions for mean and variance of the responses based on the type of robust design applications.

For the Type I, the mean and variance of the response are described by the equations, respectively:

$$\mu_{\hat{y}} = f(x, \mu_z)$$
$$\sigma_{\hat{y}}^2 = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial z_i}\right)^2 \sigma_{z_i}^2 \tag{3}$$

For the Type II, the mean and variance of the response are described by the equations, respectively:

$$\mu_{\hat{y}} = f(x)$$
$$\sigma_{\hat{y}}^2 = \sum_{i=1}^{m} \left(\frac{\partial f}{\partial x_i}\right)^2 \sigma_{x_i}^2 \tag{4}$$

Step 3: Use the compromise decision support problem (DSP) to find the robust design solution.

Du and Chen [17] proposed a statistical method to allow checking several feasibility modelling techniques for robust optimization. Kalsi et al. [18] proposed a technique to reduce the effects of uncertainty and incorporate flexibility in the design of complex engineering systems involving multiple decision-makers. Al-Widyan and Angeles [19] formulated the robust design problem based on the minimization of a norm of the covariance matrix. This matrix links the variations in performance functions with the variations in the design-environment parameters, considering the stochastic nature of the design-environment parameters.

The deterministic approaches often use the gradient information of the variations and employ the Euclidean norm method and the condition number method to improve the system robustness. Ting and Long [20] determined sensitivity Jacobian and Rayleigh quotient of the sensitivity Jacobian to measure the robustness of the system. Zhu and Ting [21] presents the theory of the performance sensitivity distribution in order to find the robust design less sensitive to variation sources. Caro et al. [22] proposed a new robust design method to dimension a mechanism and to synthesize its dimensional tolerances. Lu and Li [23] proposed a novel robust design approach to improve system robustness upon variations in design variables as well as model uncertainty.

So both of them are based on a study of impact of source variation on performance variation. These covariations are expressed by matrix and restricted to geometry versus geometry. By modelling the manufacturing and assembly process sink of geometric variations and using the resulting geometric model in numerical simulations (structure, fluid, dynamics…), the covariations can be expressed upon non geometric performances of the product and the robust design methodology can be applied.

3 Geometrical Deviations Model for Product Life Cycle

Some models of geometrical deviations for manufacturing and assembly process simulation already exist and are presented above. However, these models do not link the geometrical deviations generated from the manufacturing stage to assembly stage of product life cycle, especially integration of those into the product performance simulation. Thus, it is necessary a model of geometrical deviations consistent over all stages of the product life cycle and to link the geometrical deviations generated from manufacturing to assembly stages.

3.1 Model of Manufactured Part

The geometrical deviations model for the manufacturing stage based on the model of manufactured part [7] can describe the deviations generated and accumulated for each surface of the manufactured part relative to its nominal position. The deviation of surface j of manufactured part i realized in set-up Sj can be expressed relative to its nominal position by the Eq. (5).

$$T_{P^i,P^i_j} = -T_{Sj,P^i} + T_{Sj,P^i_j} \tag{5}$$

T_{Sj,P^i} models the positioning deviation of workpiece in set-up Sj. This deviation is a function of the MMP surfaces deviation generated by the previous set-ups, the part-holder surfaces deviations and the links part-holder/part surfaces.

T_{Sj,P^i_j} models the deviation of the machined surface j realised in set-up Sj. This deviation is expressed relative to the nominal machine. This torsor merges deviations of the surface swept by the tool and cutting local deformations.

Finally, the whole deviations generated and accumulated by the manufacturing process will be collected in the MMP, the deviations of each surface j of the manufactured part i are expressed by SDT T_{P^i,P^i_j}. The considered parameters variations in the MMP are limited and this limitation is expressed by constraints. The constraints on the part-holder surfaces deviation (CH) are relative to its quality (precision of its surface). The constraints on the machining deviations (CM) are relative to the machine capabilities. The constraint on the links between part and part-holder surfaces (CHP) represents assembly rules. At this point, the geometrical deviations generated by the manufacturing process in the manufacturing stage have been modelled.

3.2 Model of Assembled Part

Then the MMPs are assembled to make up the product with deviations. The assembly model is called model of assembled part [1] based on the gap torsor concept proposed by Bourdet and Ballot [24]. The geometrical deviation of surface j of part i relative to the product frame is expressed by the Eq. (6).

$$T_{P,P^i_j} = T_{P,P^i} + T_{P^i,P^i_j} \tag{6}$$

Where T_{P,P^i} is the positioning deviation torsor of part i relative to its nominal position in the global frame of the product. T_{P^i,P^i_j} is the torsor modelling the deviation of surface j of part i relative to part i frame, coming from the manufacturing stage. It has already been presented above as a component of MMP i. The torsor T_{P,P^i} models the positioning deviation of part i relative to the global frame of the product. It does not depend only on the deviations of the surfaces of part i, but also the links between the surfaces of part i and the surfaces of any other connected part k, the deviation of the concerned surfaces of part k and the position of part k relative to the global frame of the product. The torsor T_{P,P^i} is determined by the Eq. (7).

$$T_{P,P^i} = T_{P,P^k} + T_{P^k,P^k_n} + T_{P^k_n,P^i_m} - T_{P^i,P^i_m} \tag{7}$$

Where $T_{P^k_n,P^i_m}$ is the link torsor between surface m of MMP i (part i) and surface n of MMP k (part k). T_{P,P^k} is the positioning deviation torsor of part k, it models the positioning deviation of the part k (a subassemblied part coming from the previous set-up of the assembly process) relative to their nominal position in the global frame of the product.

In conclusion, the whole geometrical deviations of all the surfaces of the product relative to their nominal positions in the global frame of the product are collected by SDT T_{P,P^i_j}. The variation parameters of the SDT are limited and managed by the manufacturing constraints (CH, CM, CHP) and assembly constraints (CA). At this point, the geometrical deviations of the product generated by the manufacturing and assembly processes during the manufacturing and assembly stages of its life cycle have been modelled.

4 Performance Simulation of a Product with Geometrical Deviations

The geometrical deviation model of a product is generated based on the nominal model and the manufacturing and assembly processes. The geometrical deviations generated in the manufacturing and assembly stage are modelled as explained in the previous chapter.

Then we propose, in this chapter, a method that allows the integration of the geometrical deviations generated during manufacturing and assembly stage into the performance simulation of the product. The overview of this method is presented in Fig. 3.

Monte-Carlo simulation is used to create a set of m products (for example 1 million) with geometrical deviations of their surfaces, based on the geometrical deviation model. The input variables are the quality of the fixture surface and the machine tool capabilities. The simulation algorithm has been

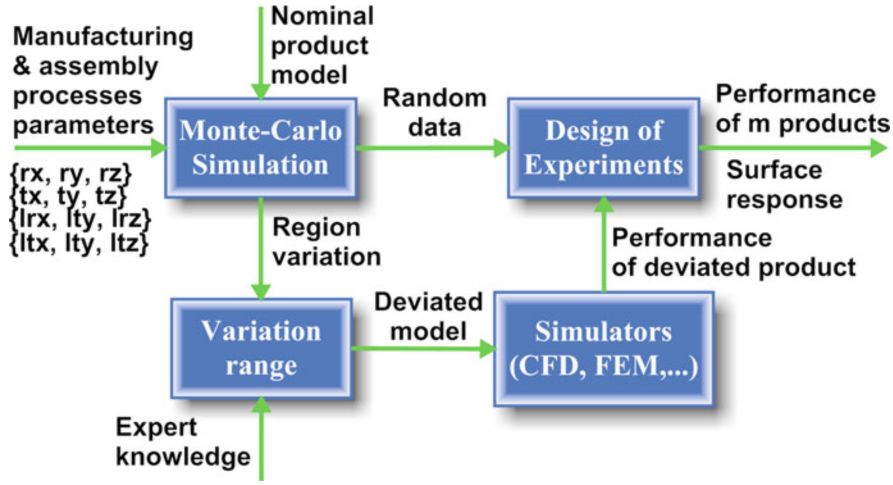


Fig. 3 Performance simulation of the product with deviations

described by Nguyen et al. [2]. From the simulation result, the product designer can know the distribution of geometrical deviations of each surface of the product.

The results of this Monte-Carlo simulation are then integrated into the performance simulation of the product. It is, however, difficult to integrate the geometrical deviations of all surfaces of the product into the performance simulation and to simulate 1 million of products with simulations lasting sometime hours (10 h for the CFD simulation treated in the next coming example). Thus, we propose to use the design of experiments (DOE) method to integrate the geometrical deviations into the performance simulation and determine the relationship between the parameters of geometrical deviations and the performance of the product.

Firstly, it is necessary to select the key geometrical parameters. These key parameters are called the factors. The strategy of selection is based on the expert knowledge. The selected parameters based on their presupposed influence on the performance of the product. Secondly, we have to define a number of levels of the factor such as 2-levels (low level, high level), 3-levels (low level, medium level, high level), etc. The level of each selected factor represents range of the variation of the factor. The variation range of the factor is determined from the result of the geometrical deviations simulation.

Then series of deviated models of the product will be created on the CAD system corresponding to the selected geometrical deviations i.e. selected factors at selected levels. These models are used to simulate the performance of the product by the way of numerical simulations (CFD simulation, FEM, etc). The response surface of the performance of the product is created by DOE method. The performance of the *m* products is then generated by the value calculation of the selected factors based on the collected data of Monte-Carlo simulation in previous phase. Then for each product its performance is calculated using surface response. From the result of the performance simulation, the product designer can verify the "real" performance of the product and asses if it satisfies the required performance of the customers.

5 Identification of Important Parameters of Variation Sources

There are many variation sources that affect the performance of the product during its life cycle such as material properties, manufacturing operations, practical environment, etc. From the result of the performance simulation of the product based on the Monte-Carlo simulation method, we propose a method that allows classifying and identifying the key parameters of variation sources within the set of manufacturing defect parameters. This method is presented in Fig. 4.

As outlined above, the collected data consist in the set of defect parameters of the manufacturing processes and the corresponding performance of the product obtain by the explained performance simulation method. The data can be described by the matrix $D = \{X, f\}$. Where $X = \left\{x_i^j\right\}_{i=1..n, j=1..m}$ is a data matrix, representing n parameters of the manufacturing processes of m product, $f = \left\{f^j\right\}_{j=1..m}$ is a data vector, representing the performance of the m products. Thus this performance depends on the parameters X of the manufacturing processes and the aim is to classify this influence.

The multivariate analysis of covariance (MANCOVA) method [25] is used, in this case, to classify the influence of the manufacturing process parameters X. This method allows determining covariance and correlation between the performance of product and each parameter of the manufacturing and assembly processes. From this result, we can use a Pareto chart to classify the important effect of parameters.

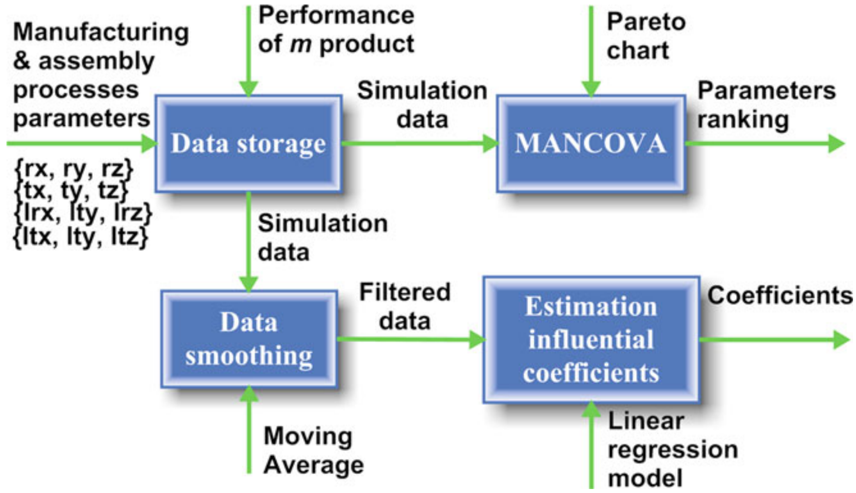


Fig. 4 Data analysis methods

The function describing the relationship between the product performance and the manufacturing process parameters $X = \{x_i\}_{i=1..n}$ can be expressed by the Eq. (8):

$$f(X) = g(x_i) + h(x_1, .., x_{i-1}, x_{i+1}, .., x_n) + q(x_i, x_j) \quad (8)$$

Where $g(x_i)$ is a function representing the trend and pattern of the relationship between product performance and the parameter x_i. $h(x_1, .., x_{i-1}, x_{i+1}, .., x_n)$ is a function representing the trend and pattern of the relationship between product performance and the manufacturing parameters $X = \{x_i\}_{i=1..n}$ except for x_i. $q(x_i, x_j)$ are function representing interaction between the parameter x_i and the rest of manufacturing parameters.

As far as X parameters has been created as independent, the function $h(x_1, .., x_{i-1}, x_{i+1}, .., x_n)$ and $q(x_i, x_j)$ can be considered as noises that influence on the relationship between the product performance and the parameter x_i when studying function $g(x_i)$. Thus, it is necessary to filter these noises.

Subsequently, data smoothing techniques, such as curve fitting, moving average, etc., is used to filter the data in order to evaluate the influence of each parameter x_i of the manufacturing processes on the performance of the product *f*. We propose, in this case, to use the moving average method to filter the data. Moving average, a data smoothing method, is to reduce noise and extract the trends and patterns of the data set. The procedure to filter the data set *D* is described by two following steps:

1. Sorting data $D_i = \left\{x_i^j, f^j\right\}_{j=1..m}$ by increase value of x_i. The data D_i includes *m* instances of parameter x_i and *m* instances of product performance *f*.
2. Filtering data by moving average method.

The data $D'_i = \left\{x_i'^j, f'^j\right\}_{j=1..m-p}$ is a filtered data of the data D_i by the moving average technique. The data $D-_i$ is described by the Eq. (9).

$$\begin{aligned} x'_k &= \frac{1}{p}\sum_{j=k}^{p+k} x_i^j \\ f'_k &= \frac{1}{p}\sum_{j=k}^{p+k} f_i^j \end{aligned} \quad (9)$$

Where *p* is a constant greater than zero defining the number of consecutive points to average. Higher values cause greater smoothing.

The aim of this stage is to reduce the noises as presented above.

The filtered data is then used to estimate the contribution of each parameter x_i to the variation of the product performance based on the linear regression model. From the smoothed data, we can determine the relationship between the variation of the product performance and each parameter x_i of the manufacturing processes. In other words, the coefficients $\frac{\partial f}{\partial x_i}$ in the Eq. (4) can be estimated by the proposed analysis methods. It is, therefore, possible to implement the robust design based on the optimization techniques for minimization of the variance of the performance of the product.

Another interesting indicator that can be subsequently calculated is the percentage $\Delta_i(\%)$ of the contribution of each parameter x_i to the variation of the product performance. The linear regression model is used to estimate the function $g_i(x)$ between each parameter x_i of the manufacturing processes and the product performance *f* based on the smoothed data $D'_i = \left\{x_i'^j, f'^j\right\}_{j=1..m-p}$. The percentage $\Delta(\%)$ of influence of the parameter x_i is then calculated by the Eq. (10).

$$\Delta_i(\%) = \frac{\Delta g_i(x)}{\Delta f} = \frac{\max\{g_i(x)\} - \min\{g_i(x)\}}{\max\{f\} - \min\{f\}} \quad (10)$$

$x \in$ variation range of x_i

The percentage $\Delta_i(\%)$ indicates how much the parameter x_i of the manufacturing processes contributes to the variation of the product performance f.

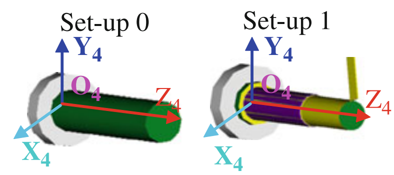


Fig. 6 Manufacturing process for the shaft of pump

6 A Case Study

6.1 *Centrifugal Pump Design*

In this chapter, a geometrical deviation model of a product during its life cycle has been presented. Then, a Monte-Carlo simulation method is used to estimate the distributions of the geometrical deviations and of the performance of the product based on this model. In order to illustrate this method, an example of a centrifugal pump is proposed (see Fig. 5). The theory of fluid mechanics used to determine the behaviour of the product is based on Lobanoff and Ross [26].

6.2 *Geometrical Deviation Model of the Centrifugal Pump*

In order to manufacture the pump, the manufacturing process, the assembly process and the associated resources are selected according to their cost and the requirements of the customers. As a result, the geometrical deviation model of this centrifugal pump coming from the manufacturing and assembly stages of its life cycle is generated by the method presented in Chapter "Method and Tools for the Effective Knowledge Management in Product Life Cycle".

For example, the shaft of the pump is realized by a turning process on a lathe machine (see Fig. 6).

The manufactured parts of the pump are then assembled according to the selected assembly process (see Fig. 7). The geometrical deviations of all surfaces of the pump are described by torsors in the model of assembled part (MAP).

In conclusion, the geometrical deviations of all surfaces of the pump relative to its nominal position in the product frame can be modelled according to the selected manufacturing and assembly process and the associated resources.

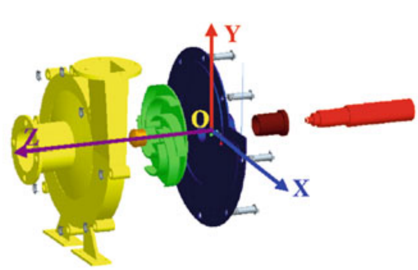


Fig. 5 The nominal model of the centrifugal pump

6.3 *Geometrical Deviation Simulation*

The Monte-Carlo simulation method is applied to simulate the geometrical deviations of the pump based on the geometrical deviation model of the pump.

Firstly it is necessary to determine the input variables of the model. In this case, the input variables are the parameters of the surface deviations torsor of the pump. The torsor parameters that represent the machining accuracy and the quality of the fixture surface, such as $rx_{i,j}$, $ry_{i,j}$, $tx_{i,j}$, $ty_{i,j}$, $tz_{i,j}$ of the surface j of the part i and $rx_{i,jSk}$, $ry_{i,jSk}$, $tx_{i,jSk}$, $ty_{i,jSk}$, $tz_{i,jSk}$ of the surface j of the fixture in the set-up k, are the input variables. In this study, these input parameters are considered as independent.

The probability distributions and the variation range of the input variables have to be determined. As far as the real distribution is unknown, a uniform distribution is chosen. The variation ranges depends on the capabilities associated resources and can be obtained by measurement [27].

For example, the variation ranges of the input parameters for the manufacturing of the shaft are shown in the Table 1.

The Monte Carlo simulation is then realized by the algorithm presented in [2] according to the selected probability distribution and variation ranges of the input parameters. Then the product designer can use the result to verify any geometrical requirements and to check the assemblability of the pump. For example, the designer can estimate the distribution of the gap between the impeller and the casing of the pump.. The distribution of the gap is shown in Fig. 7a (mean $\mu = 5.7571$ mm, standard deviation $\sigma = 0.01976$ mm). The variation range of the gap determined as 6 s range is from 5.6978 mm to 5.8164 mm.

Moreover, the designer can know the distribution of positioning deviation of each part of pump. For example, the distribution of the gap between behind plan of impeller and plan of the volute back casing (see Fig. 7b). The distribution of the impeller's centre and the distribution of the casing's centre according to two perpendicular axes X and Y are shown in Fig. 7c, d respectively.

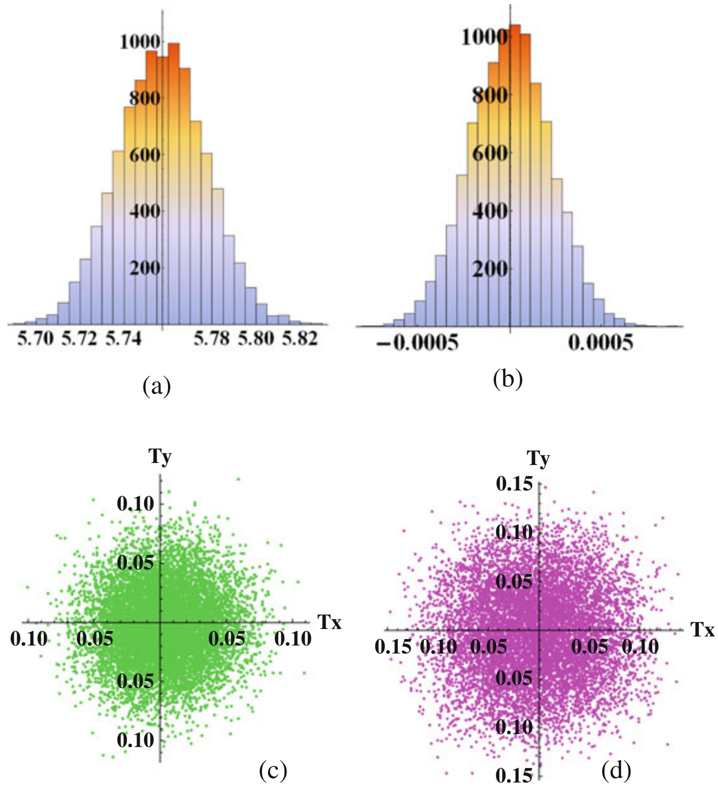


Fig. 7 Monte-Carlo simulation results

Table 1 Variation range of the input variables

Set-up 1 *Fixture*	
Plane 4,9S1	$rx_{4,9S1}$, $ry_{4,9S1}$ variation range 0.0008 $tz_{4,9S1}$ variation range 0.02
Cylinder 4,8S1	$rx_{4,8S1}$, $ry_{4,8S1}$ variation range 0.0002 $tx_{4,8S1}$, $ty_{4,8S1}$ variation range 0.01 radius $ra_{4,8S1}$ variation range 0.01
Machining	
Plan 4,5	$rx_{4,5}$, $ry_{4,5}$ variation range 0.0005 $tz_{4,5}$ variation range 0.01
Plan 4,7	$rx_{4,7}$, $ry_{4,7}$ variation range 0.00015 $tz_{4,7}$ variation range 0.02
...	...

6.4 Performance Simulation of the Centrifugal Pump

In order to integrate the geometrical deviations into the performance simulation of the product, we propose to use the design of experiments (DOE) methods. Moreover, we can find out the relationship between performance of the pump and the selected parameters of the geometrical deviations generated during its life cycle by this method (Fig. 8).

There are many parameters of the deviations that influence the performance of the pump. Thus, we propose, in this case, to choose some parameters of deviations to envisage based on the theoretical and experimental knowledge. In this example, the gap between the top surface of the impeller and the casing of the pump is selected based on the study of [28]. The translation of the impeller along two perpendicular axes X, Y in the product frame is also chosen based on the study of [29].

The design of experiments method is a full factorial design 3-levels 3-factors. The levels of each selected parameter are chosen in the following:

- High level at $+3\sigma$ (1)
- Medium level at μ (0) (average value of the parameter)
- Low level at -3σ (–1)

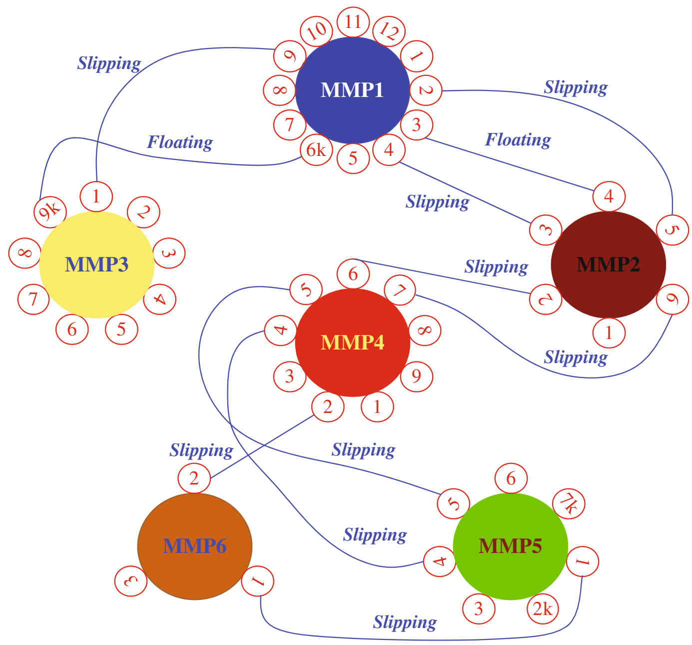


Fig. 8 Assembly graph of the pump

Table 2 The value of the selected parameters

	Gap (mm)	*Tx* (mm)	*Ty* (mm)
High level (1)	5.8164	0.08497	0.09186
Medium level (0)	5.7571	0.00295	−0.0027
Low level (–1)	5.6978	−0.07907	−0.09726

From the selected parameters of deviations of the pump, we will create the deviated CAD model of the pump with the selected deviation value as shown in Table 2. Thus 27 deviated CAD models of the pump has to be created. Then we will use them to simulate the performance of the deviated pump (here flow rate is the studied performance parameter) using a CFD software. The relationship between the performance of the pump and the selected parameters are found out by a full factorial design method. For example, in this case, mass flowrate Q of the pump function of the gap between the impeller and the casing of the pump (Gap) and the translation of the impeller relative to two perpendicular axes (Tx, Ty) is described by the Eq. (11)

$$
\begin{aligned}
\boldsymbol{Q} = {} & 1.46 \times 10^{7} - 5.023 \times 10^{6}\,\boldsymbol{Gap} + 436656.\,\boldsymbol{Gap}^{2} \\
& + 5.970 \times 10^{8}\,\boldsymbol{Tx} - 2.081 \times 10^{8}\,\boldsymbol{Gap}\,\boldsymbol{Tx} \\
& + 1.813 \times 10^{7}\,\boldsymbol{Gap}^{2}\,\boldsymbol{Tx} - 5.515 \times 10^{9}\,\boldsymbol{Tx}^{2} \\
& + 1.923 \times 10^{9}\,\boldsymbol{Gap}\,\boldsymbol{Tx}^{2} - 1.676 \times 10^{8}\,\boldsymbol{Gap}^{2}\,\boldsymbol{Tx}^{2} \\
& - 2.446 \times 10^{8}\,\boldsymbol{Ty} + 8.502 \times 10^{7}\,\boldsymbol{Gap}\,\boldsymbol{Ty} \\
& - 7.387 \times 10^{6}\,\boldsymbol{Gap}^{2}\,\boldsymbol{Ty} + 26906.4\,\boldsymbol{Tx}\,\boldsymbol{Ty} \\
& - 36301.8\,\boldsymbol{Tx}^{2}\,\boldsymbol{Ty} + 3.44957 \times 10^{9}\,\boldsymbol{Ty}^{2} \\
& - 1.2 \times 10^{9}\,\boldsymbol{Gap}\,\boldsymbol{Ty}^{2} + 1.036 \times 10^{8}\,\boldsymbol{Gap}^{2}\,\boldsymbol{Ty}^{2} \\
& - 937111.\,\boldsymbol{Tx}\,\boldsymbol{Ty}^{2} \\
& - 7.21 \times 10^{7}\,\boldsymbol{Tx}^{2}\,\boldsymbol{Ty}^{2}\ (g/s)\,.
\end{aligned}
\tag{11}
$$

The product designer not only find out the that the factors influence on the mass flowrate of the pump, but also can easily generate the population of the mass flowrate of the pump based on the distribution of the Gap, Ty and Ty. The distribution of one million pumps is shown in Fig. 9. As a result, the product designer can verify the "real" mass flowrate of the pump and compare it to the requirement of the customers. Furthermore, he can ensure that the pump he is designing have "real" mass flowrate that satisfies customers and users.

6.5 Classification of Parameters of Manufacturing and Assembly Processes

From the result of performance simulation by Monte Carlo method, the value of all the parameters of the manufacturing and assembly processes and of the performance of the pump are collected. Thus, we can calculate the covariance and correlation between the mass flowrate of the pump and each parameter of the manufacturing and assembly processes.

A Pareto chart is, then, used to point out the classification of the parameters of the manufacturing and assembly processes that affect the mass flowrate of the pump. The result of this analysis is shown in Fig. 10.

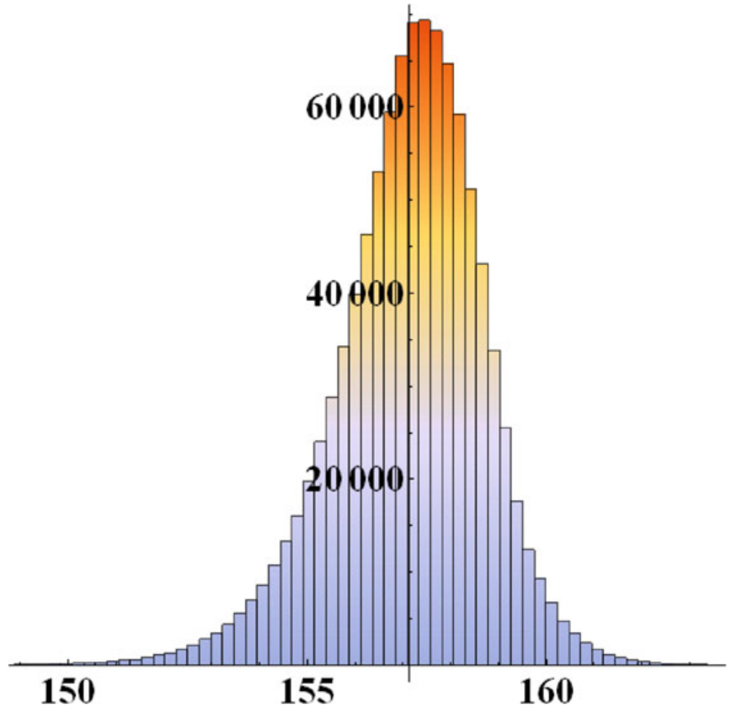
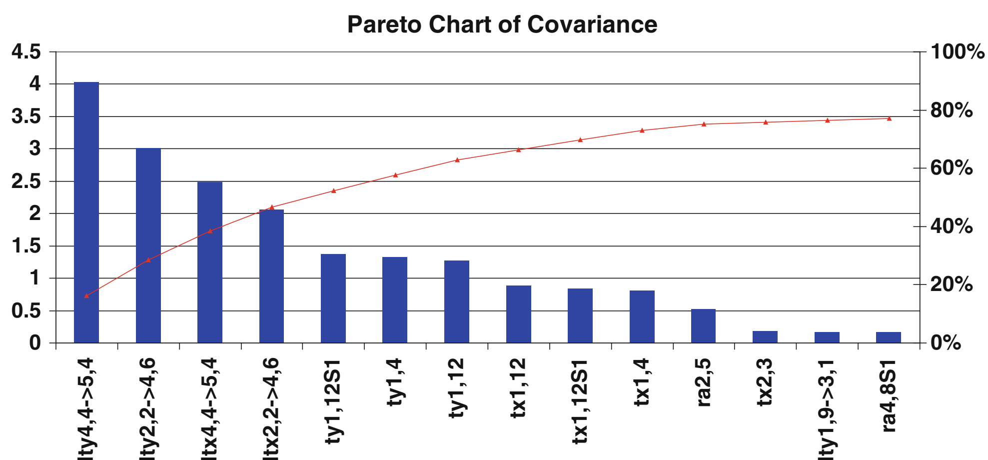


Fig. 9 Distribution of flowrate of one million pumps



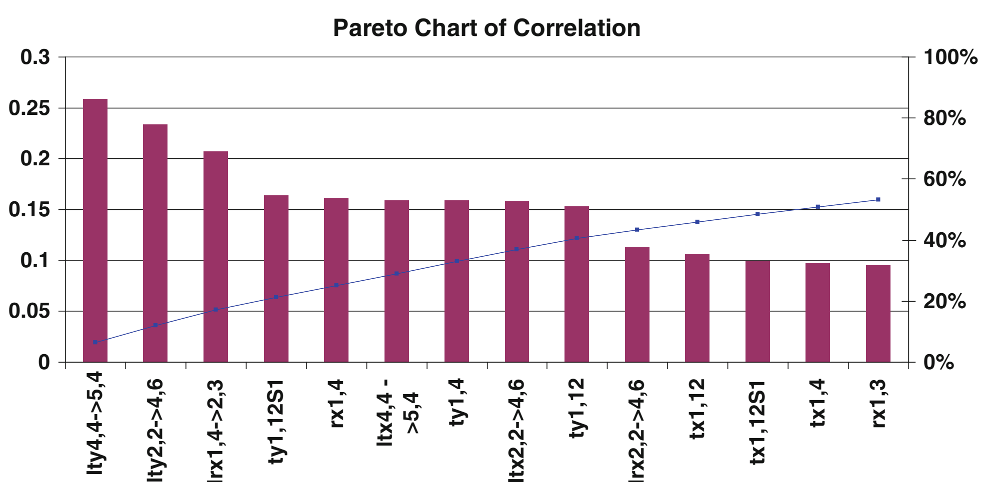


Fig. 10 Pareto chart of covariance and correlation

Table 3 The classification of parameters

No.	Classification	Covariance value	Classification	Correlation value
1	$lty_{4,4->5,4}$	4.0334	$lty_{4,4->5,4}$	0.2590
2	$lty_{2,2->4,6}$	3.0127	$lty_{2,2->4,6}$	0.2339
3	$ltx_{4,4->5,4}$	−2.4856	$lrx_{1,4->2,3}$	0.2071
4	$ltx_{2,2->4,6}$	−2.0632	$Ty_{1,12S1}$	−0.1641
5	$ty_{1,12S1}$	−1.3738	$rx_{1,4}$	0.1616
6	$ty_{1,4}$	1.3261	$ltx_{4,4->5,4}$	−0.1593
7	$ty_{1,12}$	1.2781	$ty_{1,4}$	0.1587
...	...	...	...	...

The parameters of the manufacturing and assembly processes are classified by increasing value of covariance and correlation between mass flowrate and these parameters. The result of covariance analysis is different from the result of correlation analysis. The order of the parameters in the Table 3 is thus different for covariance and correlation classification because the correlation is standardised by dividing the covariance by the standard deviation of each parameter. Thus, we can only use the correlation value to compare with the other measure of correlation. The arrangement of parameters by correlation value is used to classify the linear influence of the parameters of the manufacturing and assembly processes on the performance of the pump. The covariance value is, however, used to study simultaneous variations between performance and each parameter from their respective averages.

From the analysis result, the arrangement of the parameters' effects on the performance of the pump is created. The designer, manufacturer and assembler can know what parameters have crucial influence on the performance. For example, the set of parameters ($lty_{4,4->5,4}, lty_{2,2->4,6}, lrx_{1,4->2,3}$) are the parameters of the assembly process that have the greatest influence on the performance of the pump and the set of parameters ($ty_{1,12S1}, rx_{1,4}, ty_{1,4}, ty_{1,12}$) are the parameters of the manufacturing process.

6.6 *Identifying the Influence of Parameters of Manufacturing and Assembly Processes*

The set of values of the parameters of the manufacturing and the mass flowrate of the pump are saved over the performance simulation stage. In order to identify the influence of each parameter of the manufacturing process on the mass

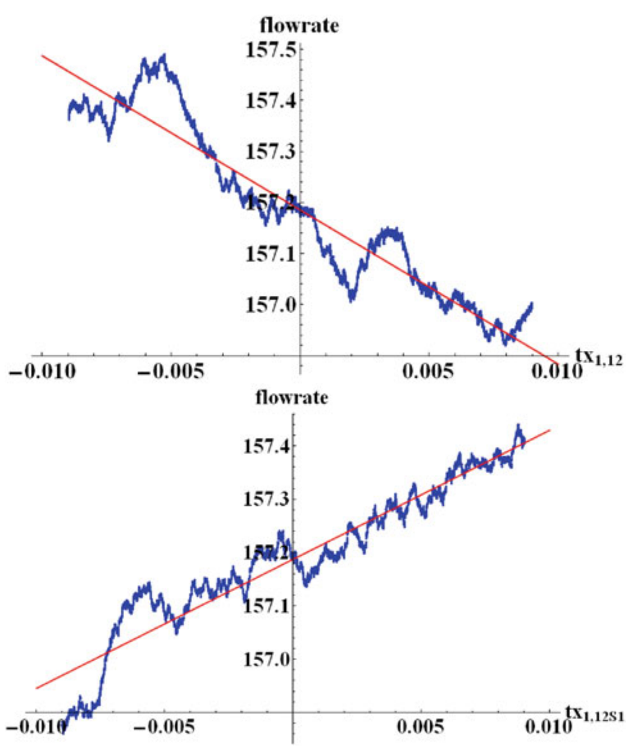


Fig. 11 Data filtered by moving average technique

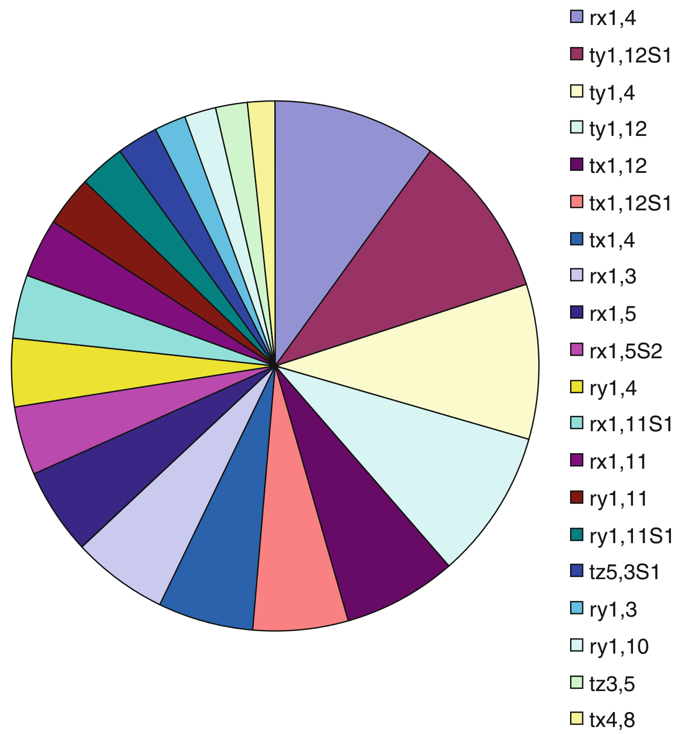


Fig. 12 Percentage of the manufacturing parameters

flowrate of the pump, data smoothing techniques is used to reduce the random noise generated by the variation of the other manufacturing parameters. This is done by moving average technique. The filtered data and linear fitting are presented in Fig. 11.

The percentage of influence of each parameter of the manufacturing processes on the mass flowrate of the pump is then calculated by the way of Eq. (9)

The result of percentage calculation is presented in Fig. 12. We can see that the manufacturing process for producing the part 1 (revolute casing back) on the main contributor to mass flowrate variation.

7 Conclusion

Today, the product designers work on the numerical model of the product within a CAD/CAM system. This model can only represent the nominal product situation. Most of the simulations to predict the behaviour and performance of the product are carried out using this model. This model, therefore, limits the ability to deal with geometrical variability occurring during the product life cycle. These variations can make the designed product not to meet fully the requirements of the customers and the users.

As a result, this chapter proposes data analysis techniques that allow classifying and identifying parameters of the variation sources that influence the performance of the product during its life cycle. As a perspective, we could contribute to calculate the variance of the performance of the complex product throughout its life cycle. Further, it could lead to the optimization of the design in order to obtain reach robust design.

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Requirements Management in Global Product Development

A Multi-dimensional Model for Structuring Stakeholder Requirements

H.-A. Crostack, S. Klute, and R. Refflinghaus

Abstract When planning and developing an intra-logistical facility, a multitude of stakeholder requirements need to be considered and implemented into solutions. This is essential to satisfy customer needs. To ensure adequate requirements management, at first the requirements have to be gathered and structured afterwards. For this purpose, a multidimensional model has been created as part of the German Collaborative Research Centre 696, sub-project A1. This model allows structuring the requirements regarding intra-logistical facilities. Based on an analysis of existing structuring methods and the identification of the stakeholders of intra-logistical facilities excerpts of the model are presented in this chapter.

Keywords Requirement · Structuring methods · Multidimensional model

1 Introduction

The revealing and realization of saving potentials are against the background of rising customer demands and cost pressure at the same time of increasing significance for companies. The fields of logistics and intra-logistics offer potentials of optimization for this purpose. In this context, an intra-logistical facility is understood to mean an in-company system of material flow which serves to convey goods from the incoming goods area through the production process and from there to the goods dispatching area. This includes systems for storage management and MRP (material requirements planning), for material transport and for order picking operations. Intra-logistical facilities make high demands on developers and manufacturers and cause high investment and operating costs. However, the use of the facility including maintenance and processes for recycling and disposal is inadequately considered during the planning, the development and purchase decision. Demands regarding these fields should be considered against the background of a customer-oriented product design. Moreover, these fields contribute to cost savings. For this purpose, it is necessary to capture and integrate requirements from a large number of fields for instance from the operator of the facility and also from the manufacturer and externals like the legislator and to realize these requirements by means of an optimized product choice and development. However, this is not achieved easily as a variety of stakeholders with divergent requirements concerning the development of the facility is yet to consider.

Basically, a qualified method to transform the requirements into appropriate solutions is the established QM-Method of Quality Function Deployment (QFD). A necessary premise for the application of this method is the information about the stakeholder requirements and their weightings. Therefore, these requirements are to be systematically surveyed and managed. As a consequence, the variety of information which has to be considered during the planning and development of intra-logistical facilities demands a structuring of these requirements before applying the QFD.

This structuring should also take the different degrees of specification of these requirements into account, since the equality or similarity of the regarded requirements is an essential premise for the application of QFD and its solutions [1]. Models for structuring provide the possibility to analyze requirements in groups in order to focus them specifically [2, 3]. Furthermore, everyone who is involved in the planning gets a summarized overview of the given information concerning the requirements. Thus, potential information deficits are revealed [4–9].

Within the German collaborative research centre 696 “Logistics on demand” [10], the project A1 “Model for

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structuring and clustering requirements for logistical facilities" deals with the development of a systematical structuring model for the planning and development of logistical facilities. Exemplarily for intra-logistical facilities a roll conveyor is used in the project. Through this, a stronger concentration on customer demands will be provided.

2 Stakeholders of Intra-logistical Facilities and Their Requirements

The term stakeholder subsumes groups, which are affected by the action of the company or are related to the company and on which the surviving of the company depends. [11, 12] Regarding intra-logistical facilities, this includes groups or persons who have demands on the planned intra-logistical facility. Referring to the classification of stakeholders according to Carrol/Näsi [13] one can distinguish between internal stakeholders which are for example operators and developers and external stakeholders, subsuming the legislator and auditors. Within the two groups of internal stakeholders, a variety of concrete stakeholders can be identified. In this context, management, purchaser, maintenance personnel, controller, distribution and operation personnel are just a few examples. These stakeholders have a great variety of divergent requirements on an intra-logistical facility.

While financial aspects, for instance low investment costs and operation costs for the facility, are predominant for the management and the controlling, for the actual "user" of this facility aspects concerning an ergonomically designed workplace and an easy handling are of foremost interest. In contrast, external stakeholders require for example the adherence to standards, a low emission and a low noise pollution. However, the requirements do not occur simultaneously but rather over the complete life cycle of an intra-logistical facility. Requirements made by the manufacturer occur thereby earlier than the ones claimed by the operator. However, this has no impact on the facility planning. Therefore, every requirement has to be considered regardless of where in the life cycle it is relevant in order to meet the stakeholder requirements. Requirements, which have not been considered during the planning, are not easily taken into consideration afterwards thus causing high costs. For example, the refitting of the facility in order to meet emission and noise requirements can be conducted.

In order to identify all stakeholders and to implement their requirements adequately within the planning of the intra-logistical facility, a suitable structuring approach is needed. This approach shall provide the possibility to detect and illustrate all requirements. In the following, existing structuring models will be introduced and evaluated.

3 Overview of Existing Structuring Methods

Literature offers a variety of approaches dealing with the topic of structuring [e.g. 14–18]. Figure 1 summarizes some of these approaches which give a good basis for individual consideration. These approaches can be differentiated due to their application respectively their purpose. Approaches, which do not deal explicitly with the structuring topic but whose application requires a structuring before, can be distinguished.

In this context, QFD can be adduced as an example. Different approaches like the KJ-method [19] or the clustering analysis do not apply any predefined structure but it is rather worked out in process. The third group of methods deals with the structuring by means of taking criteria or categories into account, whereby the number of criteria or categories of these several methods can deeply diversify. Hence, some approaches only differentiate two categories, for instance Tanaka's method who distinguishes between "hard function" concerning the technical performance of a product and "soft function" relating to the user friendliness [14].

Other approaches are more differentiated for example the approach of Pahl/Beitz which distinguishes 17 categories like assembly, mounting, safety or recycling [17]. Unfortunately, these approaches cannot be directly transferred to the field of application of intra-logistical facilities. Partial aspects respectively individual structuring methods for example the product pattern of the onion-layer-model [18] could be applied to the developed model, however, due to the complexity of the matter in consideration they were insufficient regarding the detection and structuring of the requirements. In fact, a combination, adaption and extension of already existing approaches had rather been necessary. The achieved research solutions in this context are shown in the following.

4 Model for Structuring Requirements on Intra-logistical Facilities

In order to structure the requirements, a generic model has been developed. Although being developed for the case of intra-logistics, it is generally applicable and extendable. In addition to the structuring of the requirements from the stakeholders' point of view, also time aspects have been taken into account. In this context, it has been considered on the one hand, that requirements are not simultaneously but rather in different lifecycle phases of different importance and on the other hand, that requirements are not statical but dynamical which means that they change in recourse of time. Moreover, this model contains additionally to the

Structuring method	Criteria					
Facility life cycle	Planning/ Sales	Implementation	Use	Closure		
Work	Incoming	I-point	Storage	Order picking	Dispatch	
DIN 2330	Consistency	Relation	Function			
Ehrlenspiel	Technological	Interfaces	Costs	Laws/		
	Time	Personnel	Auxiliary means	standards/patents guarantees		
Firchau	Utilitary	Factibilitary	Ecological	economical		
	Operational	Aesthetic	Communicative			
Hubka	Function	Function-related attributes	Operational attributes	Ergonomic attributes	Appearance attributes	Distribution attributes
	Delivery and planning attributes	Attributes legal compliance	Manufacturing attributes	Construction attributes	Cost-efficiency attributes	Manufacturing attributes
Industrial design	Functionality	Manufacturing	Economy	Ecology		
	Ergonomics	Aesthetics	Design Value			
DIN 31501	Servicing	Inspection	Maintenance	Improvements		
Maintenance	Control	Employees	Deployment of system	Warranty and guarantee	Documentation	Further development
KANO	Basis	Performance	Enthusiasm			
Kickermann	Component-specific	Assembly-specific	Product-specific	Interface-specific		
	Company-specific	Sector-specific	Universal			
Krusche	Purpose	Product feature	Function	Neighbouring systems	Life cycle	Company
Männel	Administration	Information	Finance	Energy	Material management	
	Personnel	Production	Sales	R&D		
Myers Shocker	Characteristics	Imageries	benefits			
Pahl Beitz	Geometry	Kinematics	Forces	Ergonomics	Substance	Signals
	Safety	Energy	Manufacturing	Control	Assembly	Transport
	Use	Maintenance	Recycling	Costs	Deadlines	
Quality control loop	Market	Concept	Draft	Testing	Manufacturing	Procurement
	Manufacturing	Final inspection	Storage	Dispatch	Maintenance	Disposal
Roth	Fixed	Target	Desired			
Sakowski	Spatial-operational	Production engineering	Technical	IT	Operational	Personnel
Servqual	Reliability	Assurance	Tangibles	Empathy	Responsiveness	
St. Gallen	Product core	Extended product	Formal product			
Tanaka	Hard function	Soft function				
Ten Hompel	System-specific criteria	Goods-specific criteria	Organisatorial criteria	Overall criteria		
	Number-relevant attributes	Geometrical and kinematic attributes	Mechanical attributes	Thermal attributes	Electrical and magnetic attributes	
VDI 225	Optical attributes	Acoustic attributes	Material and chemical attributes	Production and assembly attributes	Use, operation and maintenance attributes	
VDI 2247	Wish	Requirement				
Wögebauer	Operational tasks	Realization tasks				

Fig. 1 Overview of existing structuring methods

requirements also their fulfillment and the thereby resulting customer satisfaction and is therefore beyond the scope of the pure requirements structuring. This enables feedback between requirements and their implementation.

The shown large number of stakeholders and requirements, causing great complexity, requires a multi-dimensional model for detection and requirements structuring. Choosing the number of structuring dimensions and the division of each dimension into categories can hence generate space, in which requirements can be classified. Hereby, the corresponding dimensions and categories should be chosen in that way, that they are associable to the requirements of an intra-logistical facility. Avoiding laminations and providing independency of these categories should be considered. Classes of different dimensions should therefore be not to similar in order to prevent a comparison of these two categories from having no validity. In addition to that, classes should be independent, which means that the classification of one requirement is not based upon the results from a requirements structuring through another [7].

Furthermore, it should be taken into account, that an exact classification of requirements in one dimension is consequently not possible. They should rather be classified in an n-dimensional space, which includes all dimensions of an intra-logistical facility occurring while planning. Referring to the developed model and with respects to the field of application there are 9 dimensions to be mentioned: obligation, surroundings, economy, information, qualification, technical and functional requirements, product, weighted level of performance and customer satisfaction. Additionally, the time dimension has to be considered (Fig. 2). It may be no independent or comparable dimension to the others, but it should be taken into account, as every requirement always includes a time aspect. For example requirements can occur in the phase of planning or operating.

In addition to that, it should be regarded that dimensions like product, weighted level of performance and customer satisfaction differ from the other dimensions in terms of content. The dimension product serves for structuring the matter of consideration to which every requirement is related. In contrast, the other two dimensions serve to give feedback to the previous detected requirements. With aid of these dimensions it can be verified how and to what extent the requirements of the stakeholder are fulfilled. The model's dimensions used to detect and structure the requirements are therefore mirrored in the dimension evaluation which represents consequently the actual state whereas the former ones represent the target state. The comparison of actual and target state shows the extent to which the requirements of the stakeholders are fulfilled. From this results the customer satisfaction and its eponymous dimension. Hence, the dimensions evaluation and customer satisfaction are temporally behind the others and in the figure shifted visualized.

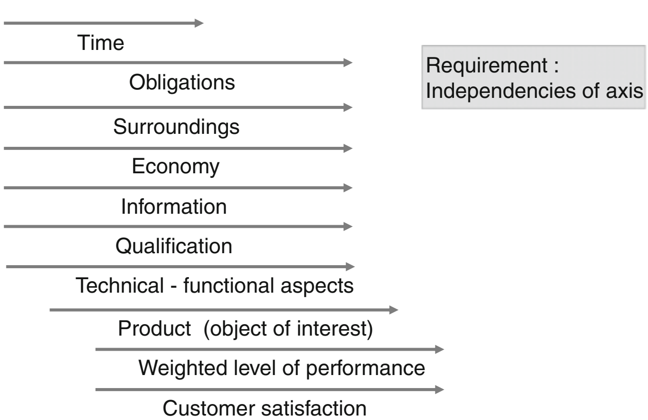

Fig. 2 Model for structuring requirements on intra-logistical facilities

The ten dimensions make it possible to structure, detect and project any requirement towards intra-logistical facilities. For this purpose, the dimensions have to be detailed and categorized further in order to ensure a topical classification of the requirements. Thus, it shall be assured that requirements, referring to different aspects, are not put into the same category or dimension.

Moreover, it shall be provided that requirements featuring different degrees of specification are adequately matched. This is crucial for the implementation of the requirements by means of the QFD for example.

In the following the dimensions obligations, surroundings, information and product will be exemplarily shown.

4.1 Structuring Requirements in Line with the Dimension "Obligations"

While planning and developing intra-logistical facilities, a multitude of requirements resulting from commitments of different stakeholders are to be considered. From this results the dimension "obligations". All requirements that need the compliance with or observance of legal aspects as well as religious or cultural moral concepts, are to be sorted into this dimension. The dimension can be structured into the categories religion/culture, laws, industrial property rights, standards/guidelines, contractual provisions and stipulations/agreements (Fig. 3).

The category religion/culture contains requirements that are based on the stakeholders' religious and/or cultural background and on values and commitments resulting from them. Moral and ethical concepts of stakeholders are among. As an example, requirements as "The logistical facility and respectively their parts must not be built by child labor." would fit into this category. This aspect will be of overriding importance, if assembly or delivery is not done in Europe.

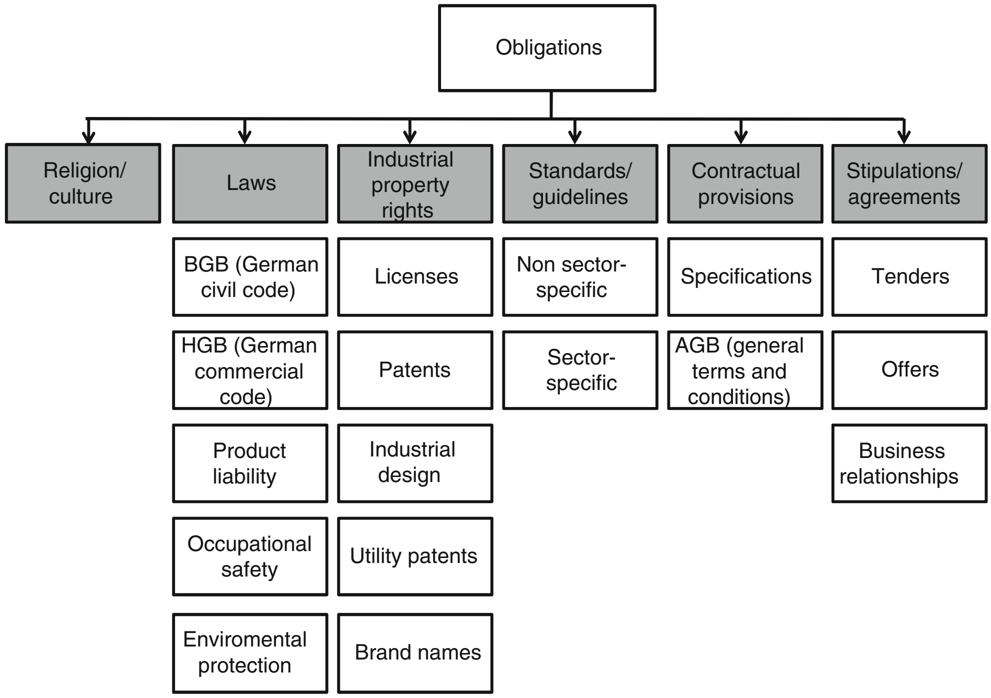

Fig. 3 Structuring requirements in line with the dimension "obligations"

Contractual provisions include requirements that derive from contracts between an enterprise and a customer. At this the aspects can be divided into specifications and AGB, depending on whether it is an individually arranged aspect or an aspect which is generally arranged by the relation between an enterprise and its customer.

Specifications are formalized descriptions of products, services or systems. By using specifications, characteristics shall be defined and quantified. Inspection and acceptance by the principal at delivery of the product or after accomplishing the service is afforded by this. In case of meeting the specifications, it is the assessment base of the payment the enterprise gets for its effort. For example material-requirements, measures and the intended use which was arranged by the enterprise and the (potential) customer belong to specifications. Specifications although do often not contain requirements which are settled by law. These have to be sorted into the category law. Requirements by law can derive from multiple laws. In particular BGB, HGB, laws of product liability, occupational safety and environmental protection can be named. Thereby, the BGB, the German civil code, regularises legal relationships between private individuals, whereas the HGB, the German commercial code, regularises legal relationships between merchants.

The AGB is the system of rules for general terms of contracts between the company and its customers. This includes aspects as rights of withdrawal, delivery, terms of payment and reservation of proprietary rights.

As said before, requirements can derive from laws. According to the legal background the requirement derives from, it can be sorted into the categories of BGB, HGB, laws of product liability, occupational safety and environmental protection. Not considering or not following the requirements of this category may result in high consequential costs and the shutdown of the production or single parts of it. This is the case, if for example laws of labor protection and environmental protection are not obeyed.

Requirements can also result from agreements which suppliers and customers arrange. These can be based on announcements and offers in which among other things, demands concerning dates or methods of delivery or even terms of payment are made, or from the type of business relation between an enterprise and its customer. "Non-formal" requirements, which are not necessarily expressed by the customer, but are anticipated and assumed because of the former business relationship, are counted among.

Requirements deriving from standards and guidelines are in another category. Therefore the requirements have to be divided into sector-specific and non-sector- specific. As an example the cross- industrial DIN EN ISO 9000 and following can be mentioned as well as the standards concerning roll-conveyors and conveying engineering, DIN EN 617 and DIN ISO 3569 in their valid versions. In the regarded case of application, the planning and construction of intra-logistical facilities, in this particular case of role-conveyors, it is to be examined which standards are to be considered and which requirements result from them.

Requirements can furthermore derive from industrial property rights. For this, a further distinction into licenses, patents, industrial designs, utility patents and brand names is possible. As in the case of not considering legal requirements, not considering requirements deriving from industrial property rights may entail severe financial consequences.

4.2 Structuring Requirements in Line with the Dimension "Surroundings"

Another dimension for structuring is the dimension "surroundings". It can be divided into the categories direct facility surroundings, resources, environment and safety. Requirements are sorted into these categories, if they do not concern the treated product but the facility's surroundings.

The category direct facility surroundings contains requirements which concern the direct surroundings of the facility. This includes for example the facility's area and the interference factors, which are devices or components whose operating or existence near the facility bear (negative) consequences for the intra-logistical facility.

The category resources contains personnel as well as material resources which are needed for manufacturing and operating the facility. The personnel resources may be of quantitative as well as of qualitative kind, which means that this category includes requirements concerning the number of the needed personnel as well as requirements concerning its qualification. Requirements concerning material resources can be differentiated by the kind of resource into for example water, gas and power.

The category environment can be divided into macro-environment and micro-environment, depending on whether the requirements are of a global kind or just concerning the close facility-environment. The first includes requirements of social, political or technological kind. Accordingly it refers to factors which cannot be influenced by the enterprise directly. Requirements concerning the micro-environment are focused at the direct facility-environment and usually can be influenced by the enterprise. This includes aspects like radiation, sonic and so on.

The third category in this dimension contains requirements concerning the facility's security. Most important hereby is the aspect of occupational safety. Requirements referring to this aim are workplace-design and the facility's construction. For this, the facility's dangerous spots are to be marked respectively to be secured, so that the danger of an accident or an injury is reduced. Figure 4 summarizes and depicts the dimension "surroundings".

4.3 Structuring Requirements in Line with the Dimension "Product"

Another possibility of structuring the requirements results from the term product respectively the product-model in the style of the onion-layer-model (Zwiebelschalenmodell) [17]. Products, in the treated case an intra-logistical facility, can be structured into the aspects product core, formal product and extended product. Requirements deriving from collaboration between the facility's components have to be considered in addition to that. This category is necessary

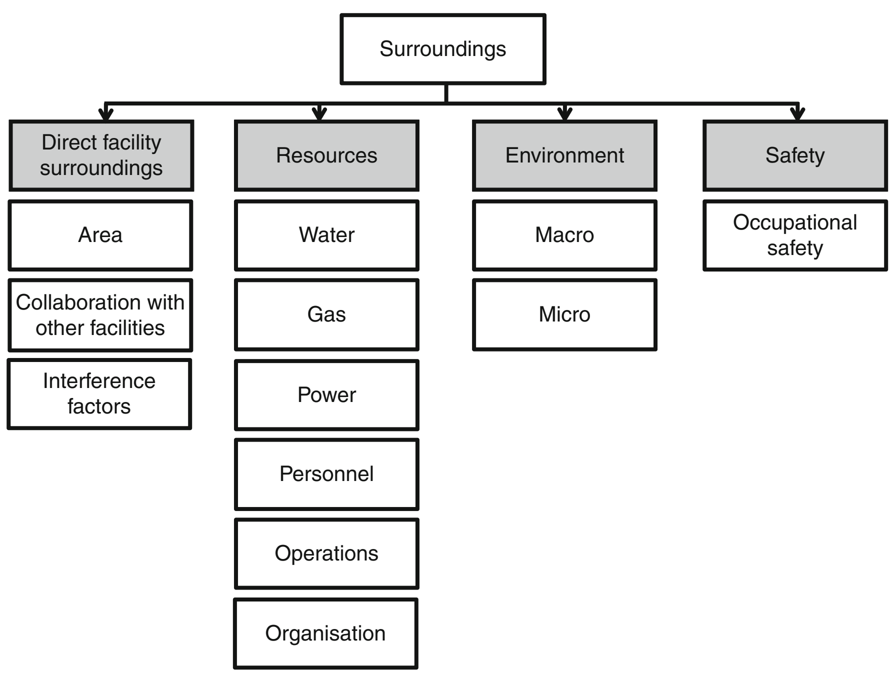

Fig. 4 Structuring requirements in line with the dimension "surroundings"

in order to consider interdependencies and compatibility between the facility's different components. The onion-layer-model (Zwiebelschalenmodell) had to be extended regarding this.

The subgroup "product core" contains requirements concerning the product's material, processing and functions. This comprises requirements concerning single assembly groups of the facility. The subcategory assembly group can be further divided into the categories mechatronical, mechanical, electrical and software. Requirements concerning for example length, diameter or even material of the used conveyors have to be sorted into the category "mechanical", while requirements concerning drive train and switches have to be sorted into the category "mechatronical". Requirements concerning controlling-software have to be sorted into the category software, while requirements concerning cables and sensors are sorted into the category "electrical".

Requirements which extend the product core are pooled in the category "formal product". Hereby a further, more slender distinction into design, packaging, ergonomics and brand name is possible. As examples for the category "formal product" of an intra-logistic facility can be named the facility's color, the brand name of its producer (or of the producers of its components) or the ergonomic design of single workstations.

Requirements concerning service or delivery have to be sorted into the subcategory "extended product". Aside of the requirements concerning guarantees, advice and maintenance of the intra-logistic facility (accessibility, maintenance intervals, spare parts supply), requirements of delivery (date of delivery, amount, packaging and so on) are also to be considered. Figure 5 depicts the parts of the dimension "product".

4.4 Structuring Requirements in Line with the Dimension "Weighted Level of Performance"

As shortly demonstrated above, this dimension differs from the dimensions which were depicted earlier. Those are set temporarily before the evaluation and gather the target state which comprises from the stakeholders' requirements for the product, in this case the intra-logistical facility. The dimension weighted level of performance instead depicts the actual state which means that in this dimension the requirements' satisfaction respectively their weighted level of performance is checked. For this it is necessary to check whether and how far requirements are met. This may on the one hand be done by a person, on the other hand by suited measurement devices. It has to be considered that a property's "true condition" is hardly measurable. For this the objective and the subjective evaluation must be differentiated. Requirements as, for example, "The conveyor-roll may not be longer than 55 mm." are measurable objectively with measurement devices. The results which are reached respectively reachable vary due to an uncertainty of measurement. That's why the "true" value can only be determined with a certain probability. Requirements like "The intra-logistical facility should be as flexible as possible." cannot be measured objectively. Those requirements respectively their fulfillment which have reference to the product as well as to services, can only be evaluated by persons. Important factors for their "subjective" evaluation are senses, feelings and their case history. When evaluating services, the ServQual-approach has to be considered additionally which evaluates based on the factors assurance, reliability, tangibles, empathy

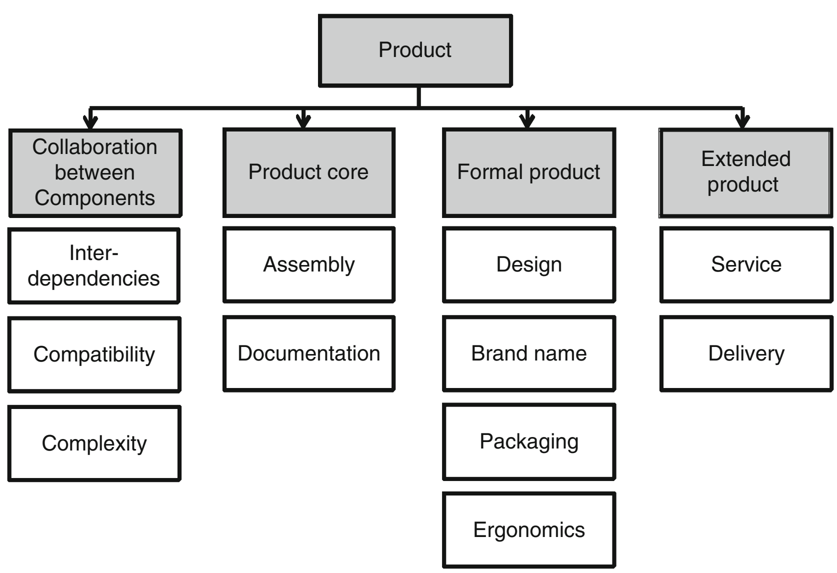

Fig. 5 Structuring requirements in line with the dimension "product"

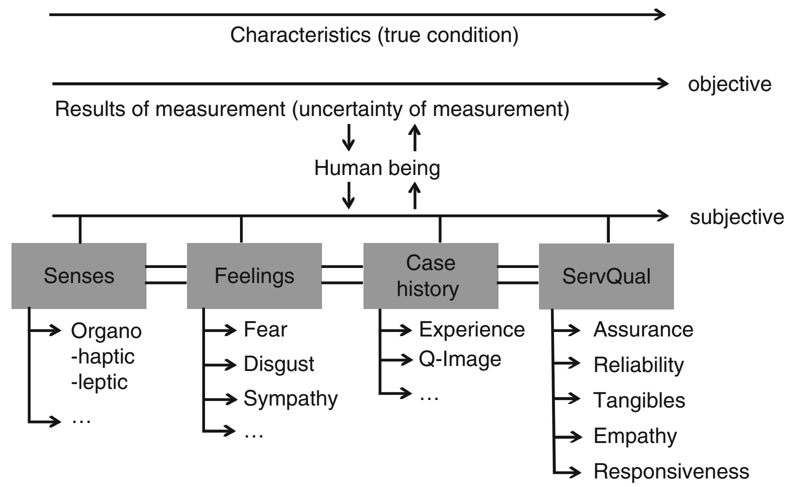

Fig. 6 Structuring requirements in line with the dimension "weighted level of performance"

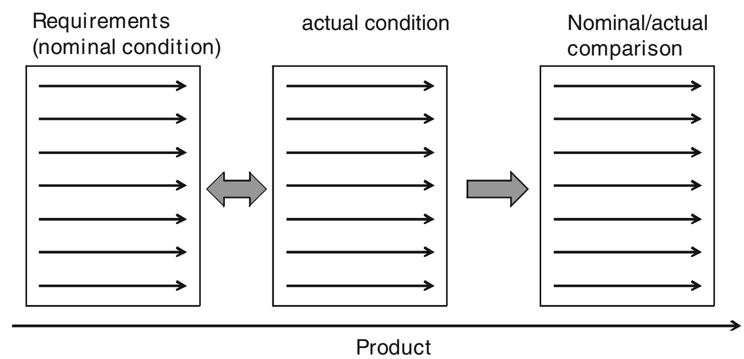

Fig. 7 Comparison between nominal and actual condition

and responsiveness [20]. In addition to that, the significance a stakeholder sees in a requirement may be important which means that the weighting of the requirement has to be considered. This is also crucial for the customer satisfaction resulting from the evaluation. This is, because the fulfillment of those requirements determines significantly the amount of customer satisfaction (Fig. 6).

According to this, this dimension contains all dimensions with which requirements can be structured and their outcomes, the actual state. This is compared to the target state to derive additional need for action, if necessary (Fig. 7).

4.5 Structuring Requirements in Line with the Dimension "Customer Satisfaction" Interfere

Information depicted in this dimension has to be distinguished from that in other dimensions. This is because there is no depiction of requirements, but a feedback to the other dimension's surveyed and structured information by depicting whether the customers are satisfied. Information for this dimension have thus to be surveyed later and result from the stakeholder's evaluation whether and how their requirements were met. Customer satisfaction thus derives from the perceived difference between expectation and performance respectively between performance-standards and the perceived quality or performance of the product. [21, 22]. A crucial aspect hereby is the importance for the stakeholders respectively their weighting of the requirement. The KANO-model can be used for this. Although, it has to be modified in order to take the weighted requirements as well as the weighted degree of satisfaction into account. According to the original model, requirements can be classified into attractive, one-dimensional and must-be-requirements. It is assumed that the correlation between fulfilling requirements and satisfaction is not necessarily linear [21, 23]. Integrating a weighting-factor although leads to the inability to depict graphs of requirements exactly. Moreover, the graphs may have a flatter or steeper progress which means that the weighting-factor causes a weaker or more intense impact of the meeting of requirements on customer satisfaction. Arrows show this fact in Fig. 8.

Fulfillment of a must-be-rated requirement is essential. Though it does not raise the satisfaction, not fulfilling this requirement will result in dissatisfaction. Attractive requirements possess in contrast to that the highest influence on customer satisfaction.

The modification's effects on the KANO-model as well as the exact determination of the graphs have to be analyzed in further research. In particular, it is essential to analyse, if the

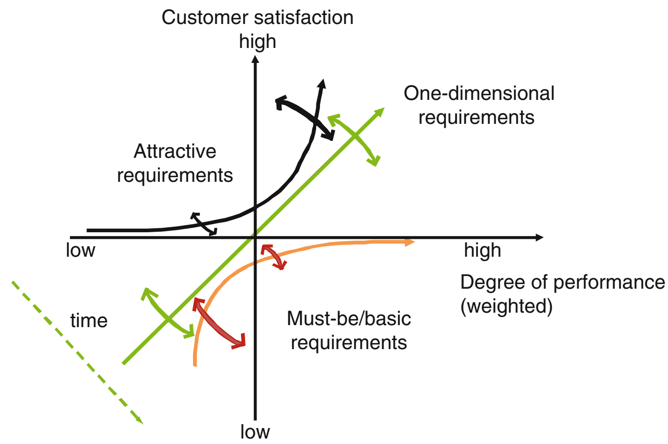

Fig. 8 KANO-Model considering weighting of requirements

currently valid definition of quality, which is until now not considered for the requirements weighting, has to be adapted to this.

Therefore the surveyed and structured requirements are assigned to the categories of the modified KANO-model to survey customer satisfaction.

Current research deals with further segmentation and details of the dimensions, the modified KANO-model as well as assignment of the requirements.

5 Visualization of Exemplary Requirements in the Model

In the following the classification of requirements into the model shall be depicted by an excerpt from the model. For this purpose, the two dimensions surroundings and product, will be exemplarily used for explanation to which requirement examples are matched. The excerpt shows the field to which every requirement concerning these both dimensions is to be matched. In addition to this, the two requirements "the facility shall be able to operate with 3 workers in shift operation" and "danger spots must not be accessible during operation time" shall be matched in this field to the categories of the dimensions. Both requirements relate to the category product core of the dimension "product" whereas in terms of the dimension "environment" the former matches the category "resources" and the latter matches the category "safety". At this, it has to be considered that the requirements match also further dimensions which are not mentioned here (Fig. 9).

6 Aim and Benefit of the Developed Model

The developed generic model for structuring requirements fulfills several purposes. Surveying all requirements concerning the matter of consideration, in the field of application of intra-logistical facilities, is possible with this model. It also serves to examine whether all requirements

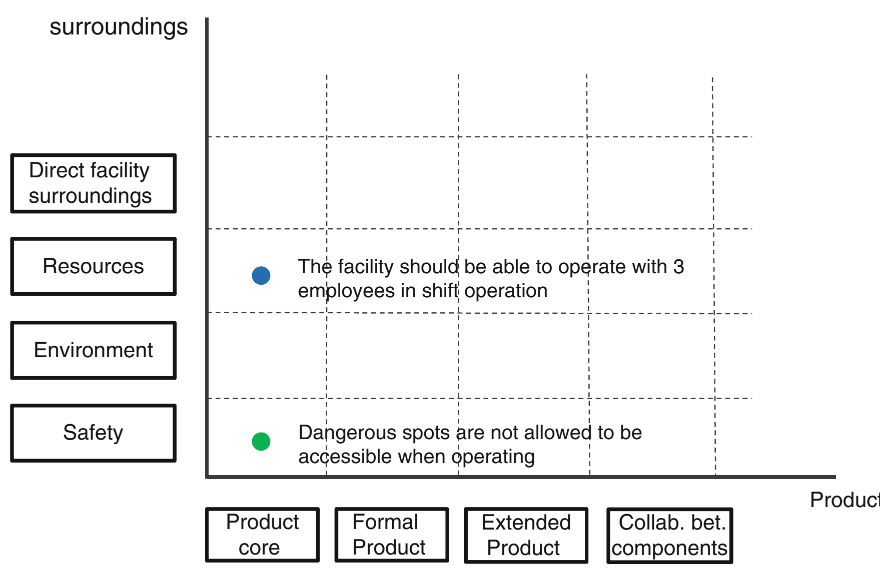

Fig. 9 Visualisation of exemplary requirements in the model

of the stakeholders are documented or whether informational deficits exist. For this, the model has been implemented for data-processing by SFB 696. The developed requirement-processing-system can show single dimensions respectively single categories of dimensions and the corresponding requirements for the current situation. By this it can be checked whether all stakeholders and their different requirements are surveyed.

Furthermore the model can be used for structuring the requirements for further use which means the implementation with QFD. Structuring the requirements before using QFD is necessary to achieve valuable results, because of the multitude of the requirements which have to be considered and which (may) exist in different degrees of specification. For this, it is possible to consider for example single groups of requirements which are single dimensions respectively categories of a dimension which show a similar or same degree of specification. This is examined in current projects of research.

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Coordinate Free Approach for the Calculation of Geometrical Requirement Variations

G. Mandil, P. Serré, A. Desrochers, A. Clement, and A. Rivière

Abstract This chapter proposes to investigate the use of a coordinate free approach for the mapping of geometrical requirement along a product life cycle. The geometry of the studied assembly is represented using a Gram matrix that is issued from a parametric model constituted of points and vectors. This parametric model is instanced for all relevant phase of the product life cycle. The calculation of instanced parameters is based on part deformation due to changing operating conditions. This calculation is carried out thanks to existing theoretical techniques. The application presented in this paper is constituted of a simple 3D case composed of 3 articulated bars disposed as a tetrahedron and subjected to some thermal expansion.

Keywords Geometrical requirement · PLM · Life cycle · Part deformation · TTRS · Metric tensor · Gram matrices · Non-Cartesian geometry

1 Introduction

In most cases, a mechanical product is subjected to thermo-mechanical loads which vary along its life cycle. These variations are inducing elastic deformations, which in turn can influence the value of the functional or geometrical requirements. Generally the useful value of a requirement is the one taken under operating conditions. However, the great majority of products are designed and represented in Computer Aided Design (CAD) systems at the assembly stage of their life cycle. Moreover, the contractual drawings are generally specified at ambient temperature. This means that in fact, the values of geometrical or functional requirements are not necessarily calculated, specified and checked under operating conditions. As a matter of fact, considering the designer point of view, several problems appear: "Does the chosen dimension allow to meet requirements under operating conditions?" or "Which dimensions must be specified on drawing to ensure a given value of the functional requirement in operation?"

A typical application that illustrates best the above idea would be that of a jet engine for which the functional requirements varies during its own lifecycle. Indeed, the clearance between the rotor blades and engine housing (or stator) of the turbine will be quite different at assembly and in operation due to the high temperature and rotation velocity to which the rotor is subjected in service. In this case, the above-mentioned designer problems should be: "Does the actual dimensions of the blades and the stator housing of the turbine ensure that there won't appear any interference under operating conditions?" and "Which dimension have to be specified at assembly to avoid any interference between the blade and the stator in operation?"

In order to provide the designer with tool for this kind of issue this paper investigates the ability of a coordinate free approach based on Gram matrix for the calculation of a functional or geometrical requirement evolution along the product life cycle. To effectively take into account the dimensions evolution along the product life cycle, the proposal approach integrates part deformation (as calculated from the stress analysis) as a variation of the parameters of the model.

This paper will introduce previous scientific contributions done in this field of research. Afterwards the coordinate free parametric model used in this research will be exposed and then an application case will be detailed.

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2 Literature Review

This section presents first some prior work done for the tolerancing of parts subjected to deformations. Afterwards geometrical models used to build the presented coordinate free approach are introduced. Finally, this section will be closed with the introduction of two configuration management concepts issued from PLM[1] community that might be useful for complex cases.

2.1 Tolerancing Flexible Parts

Here are presented prior researches that have caught the authors' attention. Firstly, Samper [1, 2] presents an approach which considers the influence of both part deformation and fit of joint into the analysis or synthesis of tolerance zones. Secondly, Cid [3] developed a model which permits the evaluation of clearances under loads using a clearance torsor introduced in [4]. This study investigates the case of the clearance between vehicle door and its frame. The representation of parts considers 3D surfaces instead of 3D volumes. Finally, Pierre [5, 6] has investigated part of the jet engine particular issue mentioned in the introduction.

2.2 Geometrical Representations

Desrochers [7] proposed the TTRS[2] model which is based on a binary and recursive association of two functional surfaces (or group of surfaces). Globally, the goal of this association is to link each functional surface to another. The result of the association process on all the functional surfaces of a part or a mechanism is generally represented as a hierarchy tree. Additionally, this approach uses the concept of MGRE[3] to obtain a mathematical representation of a given TTRS. The hierarchy tree is constructed by going through independent cycles in the kinematic graph. This theory is detailed in [7–9].

Serré [10] proposes a theory to specify univocally a geometrical problem. This is based on an information model that ensure the coherence of the specifications made by the designer and on the specification of univocal constraints between surfaces. Afterwards, in order to obtain the solution of the problem, these specifications and constraints are implemented in a coordinate free geometrical model (based on the Gram matrix [11]) to generate the algebraic relations to be solved. According to Serré this model is appropriate to describe both geometrical and technological problems. In this work Serré use the TTRS/MGRE model to describe the relative spatial positions of specifications in 3D vector space. This research proposes to use this theory for the specification and resolution of geometrical requirements.

2.3 Configuration Management

In the field of Product Life-cycle Management (PLM), some researchers have introduced interesting concepts like Zina [12] who defined the concept of "context" which could be used to define loads and environment in the proposal approach. Alternatively Eynard [13] presents an object-oriented approach to help the designing team with the transmission of both design and calculation data such as geometry, use cases, loads, etc.

3 Models Used

3.1 Context

As previously explained in [14] and [15] functional or geometrical requirements will be taken into account considering the evolution of their mean value along the product life cycle as presented in Fig. 1.

Indeed if the width of the tolerance zone is small compared to the dimension itself, then at a first order of approximation the variations of the tolerance zone width will be negligible regarding the variations of the dimension. This is

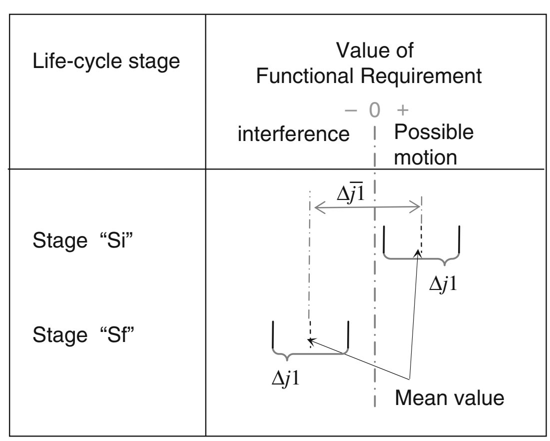

Fig. 1 Functional requirement values evolution along the product life cycle

[1] Product Life-cycle Management.

[2] Technologically and Topologically Related Surface.

[3] Minimum Geometrical Reference Element.

why, the width of the tolerance zone (noted $\Delta j1$ in Fig. 1) remain unchanged in Fig. 1 whereas the load variation induce a shift of the mean value (noted $\Delta\overline{j1}$ in Fig. 1) of the geometrical (or functional) requirement.

However, it remains necessary to include tolerance zones in the model as they provide the designer with intervals for the possible value of a requirement (due to machining uncertainties). If necessary, the width of the interval should be calculated by using existing techniques of tolerance analysis or synthesis [16–19].

The geometric dimensioning problem treated in this paper is the coupling of dimension (or geometric parameter) assignment with one or several physical effects. More specifically, as mentioned in the introduction the goal of this research is to evaluate the variation of functional or geometrical requirement due to the changing environment. This paper proposes to use a topological connector between the geometrical vectors space and some physicals vectors spaces.

3.2 Coupling Several Physical Effects Through Topology of Their Vector Space

In our study, we suppose that the topology of the mechanism is unchanged during the shift from one stage of the product life cycle to another. The topology and the geometrical (or functional) requirements define some relations between geometrical elements. In order to meet user's expectations, these relations have to be satisfied. If we consider two configurations of the same product at two different stages of its own life cycle, the topological and functional relations remain the same for both configurations. Only the values of the parameters involved in these relations are changing.

As a fist step, authors propose to map geometrical requirement evolution along the relevant stages of the product life cycle. This means that, firstly the calculation inputs are topology, initial values of dimensional parameters, and loads and the result is the value of the geometrical requirement under the considered loads. This approach is a form of geometrical requirement analysis along the product life cycle.

3.3 Proposed Approach

This paper proposes to investigate the use of a coordinate free approach for the calculations. Such an approach would be that of for a given geometry described in different coordinate systems the resulting coordinate free description would be exactly the same whatever the coordinate system is.

This choice has been motivated by the existence of generic constraints specification techniques (like in [10]) and solvers (cf. in [20]) to resolve these constraints. Authors decided to use a Gram matrix (presented below) as mathematical representation of the mechanism.

As this approach is vector space based, it becomes then necessary to obtain vectors to represent the product model. There exists several envisaged ways to obtain such vectors. Among others possibilities it is conceivable to use the TTRS/MGRE model to obtain the relative position of technological surfaces. From there it become possible to extract one or several vectors to represent the relative positions of two surfaces, parts or components. Secondly, during the early stages of the design of a product there often exists a simple geometrical representation of the product such as a skeleton from which positioning vector parameters should be extracted

3.4 Mathematical Tools

3.4.1 Gram Matrices Theory

The following definition is found in [11] : "the Gram matrix (or Gramian matrix or Gramian) of a set of vectors $\{\mathbf{x_1}, \mathbf{x_2}, \ldots, \mathbf{x_k}\}$ in an inner product space is the Hermitian matrix of inner products, whose entries are given by Eq. (1)". In this paper the names of all Gram matrices start with a "G".

$$\mathrm{G_{lm}} = <\mathbf{x_l}, \mathbf{x_m}> \tag{1}$$

A metric tensor is a particular case of Gram matrix which has its rank equal to its dimension. For example, in the 3D Euclidian space, a 3 by 3 Gram matrix which has a nonzero determinant (which is equivalent to be constituted of 3 independent vectors) is called a metric tensor. In this paper the names of all metric tensor start with an "M".

3.4.2 Application to Assemblies

In any case, this paper supposes that a vectorial representation of the assembly already exists. The vectors included in this representation will be noted $\mathbf{un_l}$ where n represents the current life-cycle stage and l is an index used to count the vectors. For example at the assembly stage noted n of the product life cycle the set of k vectors is noted : $\mathbf{Sun} = \{\mathbf{ua_1}, \mathbf{ua_2}, \ldots, \mathbf{ua_l}, \ldots, \mathbf{ua_k}\}$.

From this set of vector, and for each configuration of the product, the assembly is represented by its associated Gram matrix which will be noted **Gn** where n represents the current life-cycle stage.

3.4.3 Geometrical Requirement Calculation

Functional requirements are expressed as an algebraic relation between the vectors (or combination of vectors) used in the Gram matrix. Basically it's immediately possible to obtain the scalar product between two vectors. From there it's easy to deduce the angle between two vectors and the norm of a vector.

More generally, the geometrical requirement (noted grn at stage n) might be expressed thanks to linear combination of scalar product between vectors included in the set **Sun** above mentioned. This is presented in Eq. (2) below. where β_{lm} represent the weight of $<\mathbf{un_l},\mathbf{un_m}>$ in grn.

$$\mathrm{grn} = \sum_{1,m=1}^{k} < \beta_l\, \mathbf{un_l}, \gamma_m\, \mathbf{un_m} > = \sum_{l,m=1}^{k} \beta_l\, \mathrm{Gn}_{lm}\, \gamma_m \tag{2}$$

From Eq. (2) it's proposed the definition of two vectors β and γ that represent the weight of **Gn** in grn. Finally we the relation (3) below is obtained.

$$\mathrm{grn} = \boldsymbol{\beta} \cdot \mathbf{Gn} \cdot \boldsymbol{\gamma}^{\mathrm{T}} \tag{3}$$

3.4.4 Link Between Configurations

In order to map the evolution of the geometrical requirement along the life cycle from an initial stage i to a final stage f it become necessary to propose a way to link (or superpose) the two relevant configurations. A vectorial association of the two configurations is required in order to define their relative orientation. **Gi** and **Gf** Gram matrix (**Gi** stand for Gram matrix corresponding to the initial stage and **Gf** for Gram matrix corresponding to the final stage) are supposed to be known and the aim of the association is the calculation of a relative orientation matrix **Gif** such as defined in Eq. (4).

$$\mathrm{Gif}_{lm} = < \mathbf{ui_l}, \mathbf{uf_m} > \tag{4}$$

From there it become possible to build a Gram matrix **G**, expressed in Eq. (6), including all the vectors from the two configurations that define the set **Suif** as expressed in Eq. (5).

$$\begin{aligned} \mathbf{Suif} &= \{\mathbf{ui_1} \ldots \mathbf{ui_k}, \mathbf{uf_1}, \ldots, \mathbf{uf_k}\} \\ &= \{\mathbf{uif_1}, \mathbf{uif_2}, \ldots, \mathbf{uif_m}\} \end{aligned} \tag{5}$$

$$\mathrm{G}_{lm} = < \mathbf{uif_l}, \mathbf{uif_m} > \tag{6}$$

Moreover, in order to calculate a point deviation it's necessary to associate the configuration in an affine way. This association basically consist in assuming that a point in the two configurations has a known deviation (that could be null) during the shift from the stage a to stage b.

3.4.5 Relations Between Two Configurations

The above section pointed out the necessity of an association between the relevant configurations of a mechanism. To carry out this association it is necessary to calculate the "relative orientation Gram matrix" described in Eq. (4). The direct application of Eq. (4) is impossible because the Gram matrix approach is coordinate free. Therefore, the relative orientation has to be calculated using another technique.

Authors propose to use matrix factorisation techniques to express any **Gn** as a product specified in Eq. (7) where **Id** stands for the identity matrix.

$$\mathbf{Gn} = \mathbf{Fn}^{\mathrm{T}} \cdot \mathbf{Fn} = \mathbf{Fn}^{\mathrm{T}} \cdot \mathbf{Id} \cdot \mathbf{Fn} \tag{7}$$

Relation (7) is equivalent to (8) using Enstein's convention.

$$\mathrm{Gn}_{lm} = \mathrm{Fn}_{pl} \cdot \mathrm{Fn}_{pm} = \mathrm{Fn}_{pl} \cdot \delta_{pq} \cdot \mathrm{Fn}_{qm} \tag{8}$$

In the relation (7), **Id** can be viewed as the metric tensor of an ortho-normal basis noted **Se { e$_1$,e$_2$,e$_3$}** . From there $\mathbf{Fn}^{\mathrm{T}}$ can in turn be viewed as the transformation matrix defined in Eq. (9). As **Gn** is a Gram matrix that is positive semidefinite the terms of **Fn** remains real numbers.

$$\mathrm{un}_l = \mathrm{Fn}_{lq} \cdot \mathrm{e}_q \text{ with } n = i \text{ or } n = f \tag{9}$$

The application of relation (9) on the terms of relation (4) **Sui** and **Suf** (as defined in Sect. 3.4) finally gives the expression (10) that allows the calculation on **Gif**.

$$\begin{aligned} \mathrm{Gif}_{lm} &= < \mathrm{Fi}_{lp} \cdot \mathrm{e}_p, \mathrm{Ff}_{qm} \cdot \mathrm{e}_q > = \mathrm{Fi}_{lp} \cdot \mathrm{Ff}_{mq} < \mathrm{e}_p, \mathrm{e}_q > \\ &= \mathrm{Fi}_{lp} \cdot \mathrm{Ff}_{mq} \cdot \delta_{pq} = \mathrm{Fi}_{lp} \cdot \mathrm{Ff}_{mp} \end{aligned} \tag{10}$$

Currently, authors have envisaged the use of two factorization techniques:

- A singular value decomposition
- A Cholesky based factorisation

The affine association consists simply in an appropriate choice of a point to connect a path from initial to final configuration. The application on the case in the following section will clearly explicit this.

4 Application Case: 3 Articulated Bars in 3D

This section takes aim to propose an application of the techniques presented above on.

4.1 Case Description

This section presents the case that has been chosen for the illustration of the method. The following sections introduce elements such as: the initial geometry, case topology, the initial gram matrix, the studied geometrical requirements, the physical effect that rule part deformation and the geometrical requirement that will be followed.

4.1.1 Initial Geometry

The proposed model for this study is composed of three articulated bars disposed as a tetrahedron on a wall such as presented in Fig. 2.

The four points constituting the structure {O,A,B,C} have their initial coordinates in a global ortho-normal coordinate system (noted {**ei**,**ej**,**ek**})presented in Table 1. This coordinate matrix is noted **X0**.

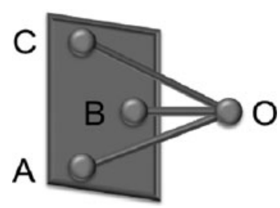

Fig. 2 Initial geometry of the case study

4.1.2 Case Topology

The topological diagram of the truss is defined thanks to the 4 vertex and 6 edges. Three of these edges are the bars represented in Fig. 2 and the three others are used to define the support wall {ABC}. The connexion between points and bars is done thanks to a connection matrix (noted **C0**) which rows contains the six bars and the four columns the {O,A,B,C} points. This matrix is presented in Table 2.

4.1.3 Initial Coordinate Free Representation

As explained in Sect. 3.4 the coordinate free approach use in the paper uses the Gram matrix that is vector based. This model induces intuitively the choice of the six vectors of the edges presented in Table 2. The Gram matrix **Gi** associated to the initial configuration is calculated using Eq. (11).

Table 1 Matrix **X0** of initial coordinates of points in a global system

Point	X coordinate (along **ei**)	Y coordinate (along **ej**)	Z coordinate (along **ek**)
O	0	0	0
A	1	0	0
B	0	1	0
C	0	0	1

Table 2 Connectivity matrix **C0**

	O	A	B	C
oa	–1	1	0	0
ob	–1	0	1	0
oc	–1	0	0	1
ab	0	1	–1	0
ac	0	1	0	–1
bc	0	0	–1	1

Table 3 Initial gram matrix **Gi**

	oa	**ob**	**oc**	**ab**	**ac**	**bc**
oa	1	0	0	–1	–1	0
ob	0	1	0	1	0	–1
oc	0	0	1	0	1	1
ab	–1	1	0	2	1	–1
ac	–1	0	1	1	2	1
bc	0	–1	1	–1	1	2

$$\mathbf{Gi} = (\mathbf{X0}^{\mathrm{T}} \cdot \mathbf{C0}^{\mathrm{T}}) \cdot (\mathbf{X0}^{\mathrm{T}} \cdot \mathbf{C0}^{\mathrm{T}})^{\mathrm{T}} \tag{11}$$

The numerical values of **Gi** are presented in Table 3.

4.1.4 Geometrical Requirements Studied

For this study, authors arbitrary propose to take into account as geometrical requirement the deviation of the vertex O and the scalar products **<oo',oa>** , **<oo',ob>** , **<oo',oc>**. O' correspond to O in the deformed configuration in accordance with Sect. 4.2

4.1.5 Physical Effect: Thermal Expansion

In accordance with the objective exposed in Sect. 3.2, authors decided to study the effect of a thermal expansion of the structure. This physical effect has been chosen for the easiness of its theoretical formulation that is given in Eq. (12). In expression (12) *li* and *lf* stands respectively for initial and final length of the bars (vectors). In the same way *ti* and *tf* are representing the initial and final temperature and α refers to the thermal expansion coefficient (typical values of α are found in the literature).

$$lf = \alpha \times li \times (tf - ti) + li \tag{12}$$

Authors assume that the wall of Fig. 2 is not subjected to thermal expansion, consequently the value of α is set to zero

Table 4 Value for thermal expansion calculation

Vector	α	*ti*	*tf*	*li*	*lf*
oa	3E–05 K^{-1}	20°C	100°C	1	1.0024
ob	3E–05 K^{-1}	20°C	100°C	1	1.0024
oc	3E–05 K^{-1}	20°C	100°C	1	1.0024
ab	0	20°C	100°C	$\sqrt{2}$	$\sqrt{2}$
ac	0	20°C	100°C	$\sqrt{2}$	$\sqrt{2}$
bc	0	20°C	100°C	$\sqrt{2}$	$\sqrt{2}$

Table 5 Final gram matrix **Gf**

	o'a'	**o'b'**	**o'c'**	**a'b'**	**a'c'**	**b'c'**
o'a'	1.0048	0.0048	0.0048	–1	–1	0
o'b'	0.0048	1.0048	0.0048	1	0	–1
o'c'	0.0048	0.0048	1.0048	0	1	1
a'b'	–1	1	0	2	1	–1
a'c'	–1	0	1	1	2	1
b'c'	0	–1	1	–1	1	2

for vectors **ab**, **ac** and **bc**. Moreover, the value of α is set at 3E–05 K^{-1} for **oa**, **ob** and **oc** vectors.

It's also supposed that the initial temperature is 20°C and the final temperature is 100°C for all the vectors involved in the configuration.

Thanks to Eq. (1), the values of initial lengths (*li)* of the bars (or the initial norm of vectors) are directly deduced from the square root of the diagonal terms of **Gi** (see in Table 3). For example: $\|\mathbf{oa}\| = \sqrt{<\mathbf{oa},\mathbf{oa}>} = \sqrt{\mathrm{Gi}_{1,1}}$.

With these hypotheses and the formulation of (12) it become possible to calculate the value of final length (*lf*) of the bars (or the final norm of vectors).

A summary of these assumptions and the result of final length calculation are presented in Table 4.

4.1.6 Geometrical Requirements

Authors propose to consider the position of the vertex O as the geometrical requirement of the case. The mapping of its evolution will be done with the measurement of the norm of the displacement vector of vertex O. This vector is noted **oo'** and its norm is calculated with: $\|\mathbf{oo'}\| = \sqrt{<\mathbf{oo'},\mathbf{oo'}>}$. Moreover, in order to compare the results with a Cartesian method, the scalar products **<oa,oo'>** **<ob,oo'>** and **<oc,oo'>** will be followed.

4.2 Calculations and Results

4.2.1 Gram Matrix of the Final Configuration

First of all, the reader is advised that the points in the final configuration (represented by the Gram matrix **Gf**) are named with primes. For example, the vertex O' in the final configuration correspond to the initial vertex O. Accordingly with Sect. 4.1 the displacement vector of vertex O is noted **oo'**.

Moreover, relation (1) allows the direct calculation of the diagonal terms of the **Gf** matrix. These values are directly the square of final lengths presented in *lf* column of Table 4. For example $\mathrm{Gf}_{1,1} = <\mathbf{o'a'},\mathbf{o'a'}> = \|\mathbf{o'a'}\|^2$.

From there, it become possible to calculate all the others terms of the matrix using the Chasles relation as in Eq. (13).

$$<\mathbf{u},\mathbf{v}> = (<\mathbf{u}+\mathbf{v},\mathbf{u}+\mathbf{v}> - <\mathbf{u},\mathbf{u}> - <\mathbf{v},\mathbf{v}>)/2 \tag{13}$$

For example the value of **<o'a',o'b'>** is given by Eq. (14) below which uses only the diagonal terms of **Gf**.

$$<\mathbf{o'a'},\mathbf{o'b'}> = - <\mathbf{a'o'},\mathbf{o'b'}> = -(<\mathbf{a'b'},\mathbf{a'b'}> - <\mathbf{a'o'},\mathbf{a'o'}> - <\mathbf{o'b'},\mathbf{o'b'}>)/2 \tag{14}$$

In the end the **Gf** matrix expression is given in Table 5.

As the treated problem here is quite simple, it's possible to carry out the calculation of the **Gf** matrix using Chasles relation (13). For more complicated cases there exists some technique [20] to solve the **Gf** matrix in accordance with geometrical or topological requirements.

4.2.2 Vectorial Association of Initial and Final Configurations

In order to respect the hypothesis of fixture for points A,B and C the Cholesky factorisation has been chosen. This criterion is only applicable to a metric tensor such as defined in Sect. 3.4. In order to obtain a metric tensor from **Gi** and **Gf** Gram matrices it's necessary to choose 3 independent vectors in the configuration to build an ortho-normal basis for the application of relation (8). As the Cholesky factorisation algorithm is recursive (see in [21]) the choice of the three vectors and their order is an important issue. In order to respect the zero expansion condition of the wall (see in Sect. 4.1) the first two vectors are chosen as part of the wall and the third is just chosen to be independent from the two others. Finally the following vectors **ab**, **ac** and **oa** (respectively **a'b'**, **a'c'** and **o'a'**) have been chosen for initial (respectively final) configuration. The following metric tensors are then calculated. **Mi** (respectively **Mf**) is associated to the basis {**ab** , **ac** , **oa**} (respectively {**a'b'** , **a'c'** , **o'a'**}) for the initial (respectively final) configuration. The **Mi** (respectively **Mf**) metric tensor is extracted from **Gi** (respectively **Gf**).

Table 6 **Mif** metric tensor

	a'b'	**a'c'**	**o'a'**
ab	2	1	–1
ac	1	2	–1
oa	–1	–1	1.0024

Table 7 **Gif** gram matrix

	o'a'	**o'b'**	**o'c'**	**a'b'**	**a'c'**	**b'c'**
oa	1.0024	0.0024	0.0024	–1	–1	0
ob	0.0024	1.0024	0.0024	1	0	–1
oc	0.0024	0.0024	1.0024	0	1	1
ab	–1	1	0	2	1	–1
ac	–1	0	1	1	2	1
bc	0	–1	1	–1	1	2

These two metric tensors are then factorised with the Cholesky technique and the **Mif** metric tensor is calculated thanks to relation (10). **Mif** values are presented in Table 6.

Again with the Chasles relation it's possible to deduce from **Mif** the global **Gif** matrix presented in Table 7.

As a first result we can notice that in **Gif** (Table 7) the last 3 columns are exactly the same as in **Gi** (Table 3). This means that the position of points A,B and C has not changed between the initial and the final stages of the experiment.

Finally the global matrix **G** representing the two configurations (Fig. 3) is obtained with the aggregation of **Gi**, **Gf** and **Gif** described in Fig. 4.

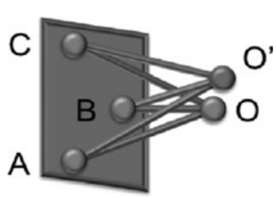

Fig. 3 Initial and final configuration of the structure

$$\mathbf{G} = \begin{array}{|c|c|}\hline \mathbf{Gi} & \mathbf{Gif} \\ \hline \mathbf{Gif}^{T} & \mathbf{Gf} \\ \hline \end{array}$$

Fig. 4 Global matrix **G** of the two configuration

4.2.3 Geometrical Requirement Calculation

In this application case, the geometrical requirement studied is the norm of displacement vector of the vertex O. This displacement is defined by the vector **oo'**. Thanks to the Chasles relation we obtain the expression (15).

$$\mathbf{oo'} = \mathbf{oa} + \mathbf{aa'} + \mathbf{a'o'} \tag{15}$$

As explained in Sect. 1.1 an affine association of the two configuration is required for the calculation of a vertex displacement. In this case it has been decided that the point A and A' are coincident (others connection points such as the middle of a bar or the barycentre of A,B,C could have been chosen). This means that **aa'** vector is null. From there the Eq. (15) become, after simplification, the relation (16).

$$\mathbf{oo'} = \mathbf{oa} - \mathbf{o'a'} \tag{16}$$

As $\|\mathbf{oo'}\| = \sqrt{<\mathbf{oo'},\mathbf{oo'}>}$, the following paragraph will detail the calculation of **<oo',oo'>**. With Chasles relation (16) we obtain the expression (17).

$$<\mathbf{oo'},\mathbf{oo'}>=<\mathbf{oa},\mathbf{oa}>+<\mathbf{o'a'},\mathbf{o'a'}> -2 <\mathbf{oa},\mathbf{o'a'}> \tag{17}$$

With the definition of **βoo'** such as in (18) relation (17) is equivalent to relation (19) below that uses the principle of relations (2) and (3).

$$\boldsymbol{\beta}\mathbf{oo'} = [1,0,0,0,0,0,-1,0,0,0,0,0] \tag{18}$$

$$<\mathbf{oo'},\mathbf{oo'}>= \boldsymbol{\beta}\mathbf{oo'} \cdot \mathbf{G} \cdot \boldsymbol{\beta}\mathbf{oo'}^{T} \tag{19}$$

The coordinates of **βoo'** are directly deduced from relation (16), using the set of vectors defined accordingly with expression (5). One can notice that **βoo'** coordinates are exactly the coefficient of the vectors of **Suif** in the linear construction of **oo'** defined in (16).

The numerical application of Eq. (19) gives results expressed in Eq. (20) below.

$$\|\mathbf{oo'}\| = \sqrt{<\mathbf{oo'},\mathbf{oo'}>} = 41\text{E}-4 \tag{20}$$

In the manner of relation (18) the following vectors Eqs. (21), (22), and (23) are defined for the calculation of **<oa,oo'> <ob,oo'>** and **<oc,oo'>** scalars products.

$$\boldsymbol{\beta}\mathbf{oa} = [1,0,0,0,0,0,0,0,0,0,0,0] \tag{21}$$

$$\boldsymbol{\beta}\mathbf{ob} = [0,1,0,0,0,0,0,0,0,0,0,0] \tag{22}$$

$$\boldsymbol{\beta}\mathbf{oc} = [0,0,1,0,0,0,0,0,0,0,0,0] \tag{23}$$

For example the calculation of **<oa,oo'>** is given by relation (24) below.

$$<\mathbf{oa},\mathbf{oo'}>= \boldsymbol{\beta}\mathbf{oa} \cdot \mathbf{G} \cdot \boldsymbol{\beta}\mathbf{oo'}^{T} \tag{24}$$

The numerical application of (24) gives results expressed in (25) below.

$$<\mathbf{oa},\mathbf{oo'}>=<\mathbf{ob},\mathbf{oo'}>=<\mathbf{oc},\mathbf{oo'}>= -2.4\text{E}-3 \tag{25}$$

The results presented in Eqs. (20) and (25) prove that a coordinate free approach is applicable for the mapping of a geometrical requirement along the product life cycle.

4.2.4 Verification with a Cartesian Method

As the application case is simple: it's constituted of few elements and only one vertex and 3 edges are subjected to some variations, authors proposed to apply a Cartesian method to solve this analysis and to compare the result obtained in the previous section.

Let's suppose that O' coordinates are $[x,y,z]$ in the initial global ortho-normal coordinate system $\{\mathbf{ei},\mathbf{ej},\mathbf{ek}\}$ of Sect. 4.1. The coordinates of points {O,A,B,C} are given in Table 1. In order to determine the coordinates of O' after thermal expansion the following Eqs. (26), (27), and (28) have to be solved.

$$\|\mathbf{o'a'}\| = \|\mathbf{o'a}\| = \sqrt{(1-x)^2 + y^2 + z^2} = 1.0024 \quad (26)$$

$$\|\mathbf{o'b'}\| = \|\mathbf{o'b}\| = \sqrt{x^2 + (1-y)^2 + z^2} = 1.0024 \quad (27)$$

$$\|\mathbf{o'c'}\| = \|\mathbf{o'c}\| = \sqrt{x^2 + y^2 + (1-z)^2} = 1.0024 \quad (28)$$

This system gives the following solutions: $\{\mathrm{x,y,z}\} = \{-2.394\mathrm{E}-3, -2.394\mathrm{E}-3, -2.394\mathrm{E}-3\}$ and $\{\mathrm{x,y,z}\} = \{0.66906, 0.66906, 0.66906\}$. The second solution has to be excluded because it changes the topology of the structure: for this solution the O' point has to pass through the wall.

This result has to be compared with those obtained in Eq. (25) because $\{\mathbf{oa}, \mathbf{ob}\ \mathbf{oc}\} = \{\mathbf{ei},\mathbf{ej},\mathbf{ek}\}$ (see in Table 3). One can see that these two methods give the same results.

5 Conclusion and Perspectives

This paper has first presented some mathematical models and tools for coordinate free approach to represent mechanisms. This model describes how to represent the mechanism in the proposed coordinate free model, how to calculate the value at a given stage of the product life-cyle and finally how to link two configurations to map the evolution of a geometrical requirement. Later on it has been shown an application of this coordinate free approach on a example. The simplicity of the chosen case allowed the authors to treat it from the beginning to the end with simple formulations and calculations that have been detailed. It also has permitted to compare and validate the furnished results with a Cartesian approach.

Globally, this paper has shown that a generic coordinate free approach is applicable for the analysis of a geometrical requirement evolution along the product life cycle.

As the approach is generic, authors propose to go further this first validation with the investigation of an application of this method on more complicated cases such as mobile mechanisms and hyperstatic mechanisms or structure. It's also proposed to use existing more efficient solvers to obtain the global matrix **G**, which allow formulating simultaneously requirements on several configurations.

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Abstract Objectives Can Become More Tangible with the Contact and Channel Model (C&CM)

A. Albers, J. Oerding, and T. Alink

Abstract Objectives in product development are abstract, thus ambiguous and are subject to interpretation of designing engineers. A throughout the process continuous modeling of objectives, can lead to a directed design problem solving. It is a common approach to control design processes through the definition of objectives. Any design activity can then be directed to the fulfillment of the objectives. This works as long as the objectives remain presents in the everyday activity of designers. Using the Contact and Channel Model (C&CM) for referencing the objectives to the designed objects gives a structure to the Product design process

Keywords Contact and channel model · Objectives · Functions · Design problem solving

1 Introduction

Commercially available solutions for structuring objectives in product development all need to challenge the same issue. Product development always begins indefinite and vague. Especially the development of new products, but also the evolution of existing products requires the handling of fuzziness.

Designers in product development are using many different models for handling the different kinds of information (calculation tools, FEA models, sketches, individual adapted excel sheets, power point graphics, text...). These models partly stem from different disciplines and thus are structured differently. Sometimes pragmatism evolved the structure of the models (e.g. freehand sketch), sometimes strict processes bear rigid models (dimensioning of dynamic loads).

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A product development process with the mechanisms of "technology push" and "market pull", with an indefinite idea or a vague market requirement.

In the case of technology push a model of the principal basic technical realization exists (e.g. PowerPoint presentation), which explains a supposed satisfaction of a requirement in a market. This model saves a set of properties, which are represented in graphical (sketch), semantic (explanation of function) or technical models (calculation of performance) and thus can be handed on for developing a product.

In the case of market pull, a requirement detected in a market exists as a model, which mostly captures the needs of a group of people of a certain size in written text format (model of the needs). How the requirements can be satisfied is not part of the model. Thus, the model saves rather requirements and functional issues than technical-design aspects.

Besides both named mechanisms the structure of enterprises leads to further differences of models applied in product development. In marketing departments so called marketing concepts are created. These concepts also are models which represent requirements, chances and risks. The marketing models serve the estimation of productivity of the product development and are occupied seldom with the possibility of technical realization and designing of functions. In relation to the later created product, these models are almost free of any shape information.

If the department of advance development is compared with the serial development department of a company also huge differences of applied models can be found. In the advance development models for conceptual implementation and studies of a possible realization are applied (e.g. simple prototypes). These models examine technical issues and are used to clarify basic questions of possible realization of later manufacturing processes. On the other hand in the serial development the shape of the product is determined exactly and the "design freeze" takes place. Detail questions of manufacturing processes are clarified. Thus, not only the detail geometry is determined but also how the product can be manufactured efficiently.

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These principal examples show that within the different activities of a product development process very different models are applied. Characteristic therefore is that product development begins with abstract indefinite objectives, functions and models. Throughout the course of product development the objectives and also the models become more tangible and more concrete. Yet, this course is determined by an individual process of creative steps, where solutions are sought, analyzed through steps of validation and checked for the correspondence with the objectives [1].

Thus, there is a demand for a system of objectives for PD, which shall be the only location of where objectives are fixed and documented. This system of objectives requires to be represented by a model that is applicable in any phase of the process in order to keep transparent the objectives for controlling the individual course of any PD project.

Reasons of why present approaches remained isolated applications or why holistic approaches failed are addressed in the next section. The systematic management of objectives requires either an integrated model, which can represent fuzzy as well as concrete representations or a model that allows transferring different models into each other. The Contact and Channel Model (C&CM) qualifies for exactly performing this need.

2 Background

2.1 System of Product Engineering

The system of product engineering consists of the interaction of three systems: system of objectives, operation system and system of objects. Figure 1 shows the hierarchical concept of the three systems. The system of product engineering comprises all artifacts and people working on the design task with all the resources available. The only active sub system is the operation system. In the system of objectives any objectives of the involved persons are stored as a networked system (objective: *make money* as well as must be *long lasting*). The system of object contains all the results generated to satisfy the various objectives and sub-objectives. The approach goes back to [2] and [3] when the first works on structuring product development with a systemic approach led to the description on system of objectives, system of objects and operation system.

The course of a product development is shown in Fig, 2. The figure shows the flow of information between the systems. The only active system is the operation system. The operation system receives information on markets (market pull) or technical potentials (technology push) (1a in Fig. 2) and hereof creates a system of objectives (1), thus prescribes the objectives to itself (2). The operation system creates objects that are structured in the system of objects (3) that potentially satisfies the set defined objectives.

Thereon up the operation system checks whether the objectives documented in the system of objectives correspond (4) with the properties of the creatively generated object. If this is true, the product development is successfully completed (5) and a product can leave the system of product engineering (Fig. 1). If there are detected discrepancies between system of objects and system of objectives two types of measures can be taken: 1st the system of objects is changed or improved in order to satisfy the objectives (3), or 2nd the system of objectives is changed (1), i.e. new objectives are defined or existing ones are modified.

2.1.1 Design Process of a Pole Pruner

Throughout this chapter the issue will be explained by means of the product development project of a pole pruner (see Fig. 3). The objective of the product development was *easy and light cut off of wooden branches in huge height.* The active operation system are the design engineers of

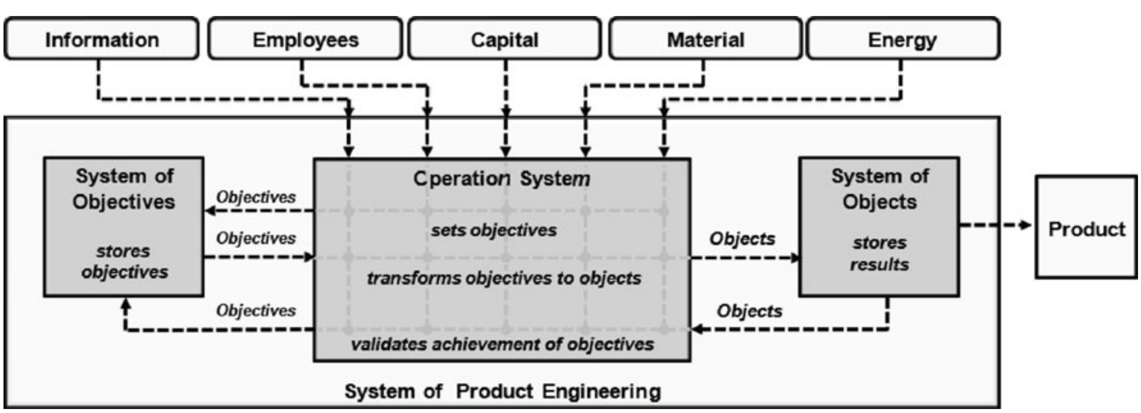

Fig. 1 System of product engineering

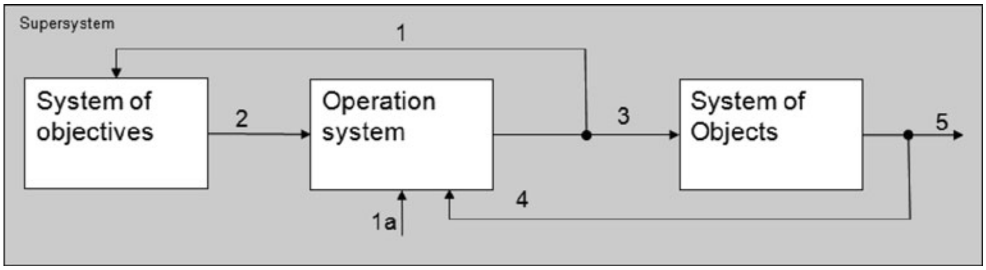

Fig. 2 Control diagram for the interacting systems of product engineering

Fig. 3 Pole pruner and wearing device while in use

the company working on this project and all the resources (simulation tools, rapid prototyping, drawing and sketching tools, . . .) they are using in order to complete the task.

Yet, the pole pruner and the backpack wearing device (see Fig. 3) are product of the system of objects of the product development project. The selling of the pole pruner confirms that the *pole pruner* corresponds closely with the given objective of *easy and light cut off of wooden branches in huge height.* Customers accept the product as satisfactory to their objectives. However, there is a potential discontent with the functions of the pole pruner. The functions that are fulfilled by the pole pruner could better satisfy the objective.

In this chapter the development process of the pole pruner is regarded in order to explain the introduced approach to structure and keep transparent the objectives of a product development process.

2.1.2 Insight as the Smallest Part of Product Development

Basis for the understanding of the approach introduced in this chapter is importance of models (e.g. [4]). Any operation requires the medium "model": Any operation requires the insight of a discrepancy between an objective that shall be reached and a current state does not satisfy the objective. However, the comprehension of the discrepancy takes place relatively to certain subjects (e.g. designers), further selective (influence of other objectives) and timely bordered to its original.

Within the proposed model of objectives, operation- and system of objects in product development any insight generated by the operation system emerges through the comprehension of a discrepancy between the conceived objectives and an object that was implemented for satisfying the objective. In the case of the pole pruner that is the potential discontent with the current functions. Not until this discontent is comprehended an evolution of the pole pruner will take place. Thus, the conceived objective is a mental image, an abstraction of the anticipated state in future.

The operation system then hypothetically generates a system of objects that is based on assumptions. The hypothetically generated object must then be concretized. The operation system stepwise validates the object using the resources that are available. Finally the operation system implements the hypothetically generated object in a concrete object, the product (the new generation of a pole pruner). This object manifests the insights that were gained through the validation step (see in Fig. 4).

Product development is the defining of product properties that correspond with the objectives of the PD project. Therefore within the process models that describe the product on different levels of abstraction are generated. These models allow for a discrete changeover between objectives and the final product. These models shall provide more security to the course of the process.

The functional description of a product in this context is very important. In most approaches to design processes (e.g. [5]) functions represent concretely formulated customer wishes and represent the actions a product shall perform (they are also part of the system of objectives) in order to meet the determined objective. Functional descriptions exist on different levels of abstraction. They always have a direct relation to the shape that is generated for their fulfillment. Thus, functional descriptions often include indication on the shape. The concrete shape is generated in order to fulfill functions and thus objectives. However, there exist various

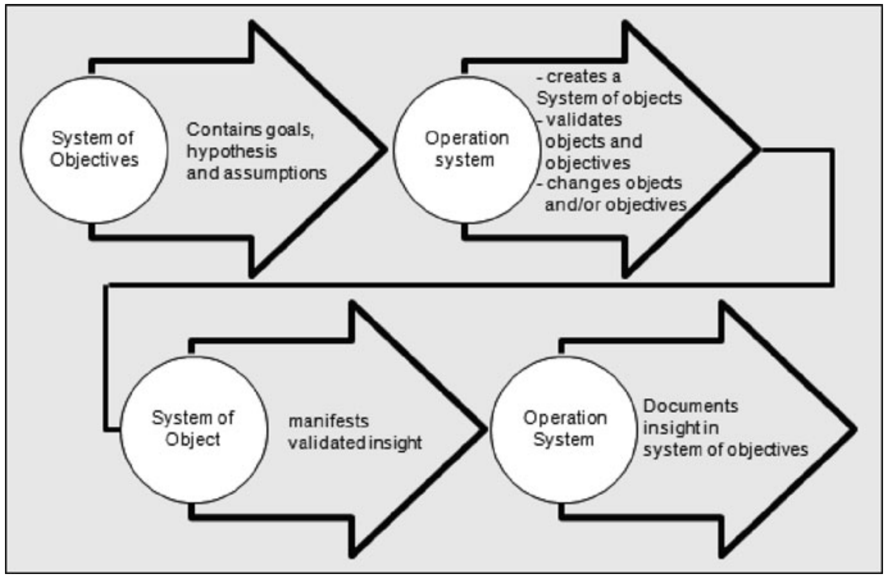

Fig. 4 Sequence of steps leading to advance in PD

concepts of function [6], which refer to different levels of abstraction and different applications

The definition of product properties, which bear a considerable innovation are mostly based on hypothesis, assumptions or interpretations, because they assume that those properties implement a function that satisfies the intended objective of the project. An always recurring element is e.g. the interpretation of customer wishes or the assumption of a certain durability of a component. The prediction of properties of components, e.g. by means of calculation models has long ago found the way into product development. An enterprise gaining or keeping a competitive position affords to work on the frontiers of predictive methods. In any case, models are the basis for the calculations and prediction of product properties. A direct consequence hereof is an ever present insecurity of the transferability of the prediction results into the real world.

Characteristic for product development is that product models are generated based on such hypothesis, assumption or interpretations. Hence, essential part of product development must be the validation of those models. The validation performs to alignment of the posted hypothesis, assumption or interpretation with the objective for the PD project.

This step of validation can be conducted logically or empirically. Validation is the checking of the properties of a system of objects that was implemented by the operation system in reference to the intended functions that are claimed in the system of objectives. Result of the validation is an insight. From this insight further steps (e.g. more specific objectives) are derived for the process of product development.

The interrelation of hypothesis, validation and insight can then be applied to cover up the deviations in product development processes form the planning situation. Prescriptive methods and models for product development processes are limited in their efficiency as planning is always based on assumptions that need to be validated throughout the run of the process [7].

Within the planning of product development processes this insight is of heavy weight. A central element of the operation system of product development thus is the activity of validation. Validation is the means for gaining insight and thus the key to innovation. Product development is a stepwise iterative procedure. Any step requires a validation of the presumed assumptions if a target oriented following step is afforded.

Compared to other works [8] the system of objectives (not the objects of the process) is the core of product development. Well defined hypothesis and efficient strategies for validation represent an efficient product development. Product development should always be oriented to the system of objective.

If the system of objects is set into the focus of product development, the process is oriented on a current result of the process, thus an efficient planning is not granted any more. Any activity in product development is determined through the control circle of objective and object as the source of insight.

2.1.3 Objectives in Product Development

As long as product developing enterprises are subject to condition of free market economy, they are organized to objectives.

Definition of objective: An objective is a state in the future, whose attainability is aimed for.

The origination of objectives results in various forms of appearance. Objectives e.g. emerge during meetings. If there is a recorder it still is not assured that he/she documents the content of the discussion objectively. Furthermore the question of where these journals travel to is unanswered. Objective often exist implicitly, i.e. they are not articulated and are not documented in any other way. Yet, their satisfaction is required. E.g. is the objective *achieve certain durability for a component* not satisfied until the evidence of durability is shown proof? How the evidence is generated is not explicitly specified. The test engineer has to model the system adequately and to lay-up the test correctly. Thus, a first fuzziness of objectives becomes clear: It cannot be stated if the model of objectives is complete until all the relevant sub-objectives are explored and formulated.

Objectives in product development must be expressed in written (e.g.: we want to increase our market share about 5%). This can be held true for strategic objectives as well as for all other objectives (e.g. technical objectives: component weight must be below 8 kg; economic objectives: benefit margin must be above 20%). Written text is always interpretable and gives room for interpretation in abstraction [4]. This second source of fuzziness results in that it can never be stated that an objective was understood precisely. A third source of fuzziness lies in the description of objectives. Objectives are intended future states, future is not predictable.

The handling of this fuzziness can only succeed, if a consciousness for it is evolved. This consciousness can only be generated if the interrelations within the system of product development are transparently displayed.

If the most understandable and comprehensive documentation of objectives is assured, the development of system of objects can be organized according to them. Only a clear formulation of objectives enables an assessment of the quality of the found solution. If it is requested to make traceable decisions, the application of system of objectives is inevitable. The formulation and networking of objectives in a system of objective affords a structure purporting the filling of objectives. The structure to organize the objectives used in this work is the Contact and Channel Model introduced in the main section of this chapter.

2.1.4 System of Objectives of Product Development

Basically the system of objectives is established in order to save and network information. The system of objectives is created by the operation system (designer, manager…) involved in the product development.

Definition system of objectives [9]: Within the system of objectives all objectives, boundary conditions, interdependencies are described. The system of objectives is a passive, normative system and contains the explicit documentation of all information required for the realization of a product. The Elements of the system of objectives must be traceable and reasoned. Changes within the system of objectives are documented together with their reason. The objective only contains information, it does not contain and physical objects. The system of objectives is the storage of the insights and the only binding location for the planning of the product development process.

The system of objectives of product development underlies a permanent growth and change and therewith is a dynamic, non-deterministic system. The change comprises a permanent evaluation of the objectives. Objectives in product development depend on numerous factors, which also underlie a permanent change. The system of objectives must be created in such a manner that these permanent changes can be traced at any time, if the company wants to sell successful products. An inherent consequence of the permanent change is the difficulty of caring for and over viewing all objectives.

It can be assumed that objectives have existed if any design process begins [2]. This is true for the basic configuration of the objectives. The specification of these mostly vague and indefinite objectives is a core element of the product development process. Beginning in the early phase, anything in product development is about acquisition of information. The importance of saving the information efficiently is enormous. Therefore a system of objectives is established.

The loss of why an objective becomes unreachable does not result in a loss of information in the system of objectives. Even more the reasons for the loss should be documented. Thus, the system of objectives is an open system.

A further aspect of the acquisition of information is the determination of objectives and requirements. Numerous research essays have been written, [10–12]. A system of objectives describes a future state, which is longed for. This model of the future state is established with full conscience that the relations of the future are mostly unknown. E.g. the strategies of competitors are unknown. Reactions of customers and of the society onto new market situations remain speculation during the development of new products. The insecurity can extended onto the aspect of a possible technical realization. The development of technical system is always characterized through assumptions, which are validated in the course of the process.

Based on the heuristic character and the complexity of product development, the performance of current computer systems it is up to today not possible to model the whole system of objectives with a single tool. Isolated application exist [13].

2.1.5 Operation System of Product Development

Product development has the main function to cover up a customer need and satisfy the latter through the creation of a

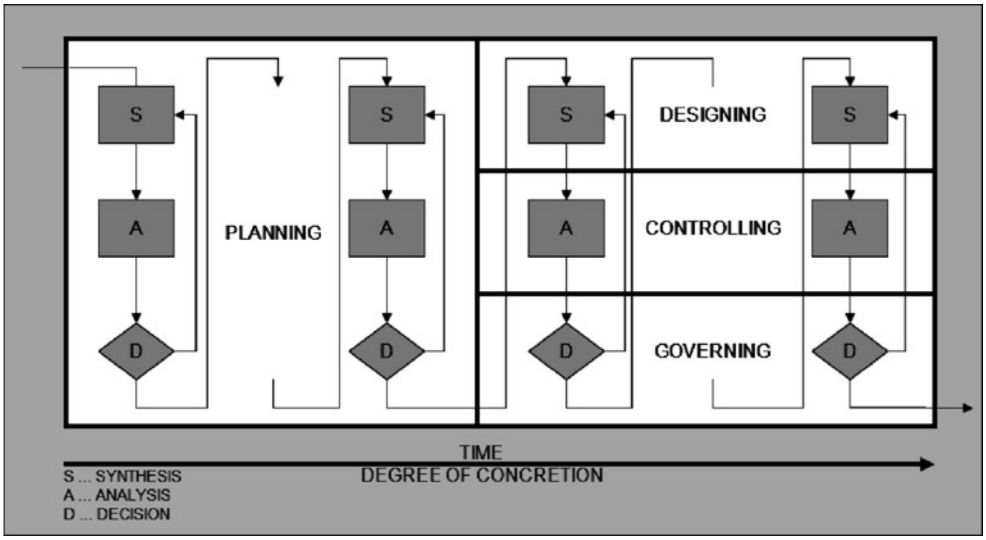

Fig. 5 Basic functions of purpose-rational action [2]

product. This task is performed by the operation system. The operation system of product development is not limited to the boundary of the department of product development of a company. The definition is as follows [9]:

Operation systems are socio-technical systems, which contain structured, networked activities for the transformation of a system of objectives into a system of objects. Activities are the performance unit of an operation system. They are composed of actions, performing resources, usable resources and timely interdependencies. Activities are networked actions and are superior performing unit of the operation system. Larger connected activities form a process. Actions transform one state into another whereas there is no cause for a further decomposition. The operation system builds up the system of objectives as well as the system of objects. Figure 5 shows how the operation system acts in the basic function of purpose-rational action [2]. This basic scheme can be applied to any problem. Many problem solving processes like of the systems engineering approach [14] build up on this scheme. Yet, the paper in hand focuses on problems of product development. I.e. the first step of a synthesis takes place on an insufficient basis of information.

The operation system is a concrete, artificial system. It is build up by humans for a distinct purpose. Yet, the operation system is a socio-technical system. Humans are elements of the operation system and thus inevitable cultural, historical and personal influences are becoming factors of the system. In pure technical system, which is also artificial, cultural, historical and personal factors do not influence.

Operation systems are highly dynamical because of the presence of humans. The function of the system changes permanently as well as the structure of the system. The permanent change also comprises the relations between the elements of the system. The operation system has the ability to generate itself. The acquisition of new employees from other competitive operation systems and the purchase of a new tool for manufacturing of prototypes exemplify this issue.

Objects that were created by the operation system can become elements of the operation system. The prototype as a means to gain insight in different activities exemplifies this special dynamic of the operation system. E.g. a first prototype of the pole pruner was created as an object in the system of objects for the objective of “device must have an ergonomic handling”. The prototype allowed validating whether the requirement of ergonomics can be satisfied. After proofing this objective as satisfied the prototype of the pole pruner can be used for e.g. for commercial purposes, thus is a resource of the operation system.

This special dynamic of the operation system causes the system to be stochastic. The stochastic nature of operation systems is the reason for the failing of prescriptive approaches in product development processes [9]. The prescriptive approach can not deal with the dynamic of the system. The dynamic is also the reason for the declaration that any product development process is a unique process and thus is not comparable to other processes. Due to the stochastic, dynamic and objective setting character it is difficult to localize all elements of the operation system. Through concepts like “Open Innovation” [8] the department of product development is no longer restricted to one company. Many partner companies work together at the solution of a task in different sections of the product development process. The task is presumably the only aspect that localizes the operation system. The operation system comprises all elements working at the same task. Operation systems exist on different levels of hierarchy. The smallest part is a single person with a system of objectives and the resources for the implementation of the objectives in a system of objects.

2.1.6 System of Objects of Product Development

System of objects is a passive system. Its definition bases on the former thing system (german: sachsystem) of [2]. The system of objects contains technical structures. They are concrete and artificial systems, which are created by humans for an intended purpose. The system of objects is an open systems, which is mostly are dynamic. The system of objects can be situated in arbitrary environment and hold accordant attributes. A list of all specific system of objects would go beyond the scope of this chapter. But sketches, CAD-models, physical or virtual prototypes as well as functional descriptions are system of objects. The product that is sold by the company and that allows earning money is a special type of object, as it is the only object of a product development that leaves the system of product engineering (Fig. 1).

Definition of system of objects [14]: System of objects are artifacts of the system of product engineering. The purpose of an object in the system of objects is described in the corresponding objectives system. Within product development for any system of objects there must exist an associated objective. Intermediate results of product development are objects that are related in the system of objects. Up to the final product the other objects in the system of objects serve the gaining of insight and thus the derivation of more specific objectives. This situation specific system of object is particular to the different activities of product development. Also immaterial artifacts like e.g. software can be objects in the system of objects.

2.2 Process of Product Development

In product development technical systems are created in order to fulfill an intended function. Designers create parts, technical artifacts, products that fulfill a certain function in order to satisfy a specific objective. Functions and objectives are abstract. Functions and objectives can only be anticipated through description. The functions of a product determine what the product is created for. Thus, the intended functions of a product correspond with the objective for the product development.

2.2.1 Functions and Objectives

A function of a technical system can be determined through the transferring of one state into another (see Fig. 6). Any system fulfilling a function conducts such a transfer. The function of a pole pruner (Fig. 3) is *cut off branch*.

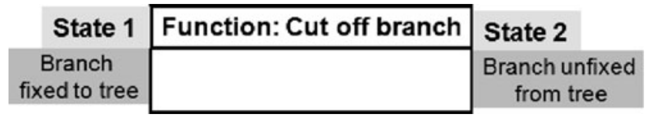

Fig. 6 Transfer of states characterizing a technical function

The function is the relation between the input and the output state. State 1 for the pole pruner is *branch is fixed to the tree* state 2 is *branch is unfixed to the tree* (the intended state: objective).

Objectives of a product development corresponds with the quality (or performance) of a function. The value for the quality of a function is given through the objective value. Within the product development of the pole pruner an objective is to *allow for an easy and light cut through*. The function *cut off branch* must be conducted with as less force as possible in order to gain as much comfort as possible to the user. Thus, the quality of the function *cut off branch* is determined by the force value the user needs for cutting through the branch.

An objective solely describes the intended future state, whereas into the term of a function also the original state is incorporated. In contrast to the objective, the function *cut off branch* has to consider that the branch is fixed to the tree. A device fulfilling this function is designed under consideration of both states: the present situation (state1) and the objective (state2).

2.2.2 Abstract Objectives and Functions do Get Lost in Product Development

In order to control a product development process, objectives shall be kept transparent at any time [15]. A transparent and concretely localizable system of objectives that is closely referenced to the objects, enhances the security of the product development process. Many product development processes fail due to a lack of objective orientation and transparency [15]. The problem of the system of objects in the focus of product development is ubiquitous.

There is no tool to model objectives from the beginning until the end of a product development process in one unique manner. Objectives are formulated abstractly, thus do not have a concrete location and can hardly be integrated into concrete representations of the product. This is a result of the different structure of applied models. Thus, abstract objectives are getting lost throughout the process or are underlying a huge rang of interpretation.

The Contact and Channel Model [16] helps structuring objectives throughout the process as the elements WSP and CSS can be assigned to functions and their objective values as well as to concrete locations.

3 A Continuous Representation of Objctives with C&CM

3.1 Contact and Channel Model (C&CM)

As argued in the previous sections, designers require methods that support their customary way of thinking, thus to enable them to come up with new ideas while keeping transparent the objectives of their design task.

Using C&CM allows isolating an individual problem from the remaining technical system at any time of the design process, at any level of detail. The designer can then solve and integrate the solution into the entire system to check the overall effects of the changes. C&CM does not only serve the description of the objects in the system of objects as an analytic tool.

The C&CM provides a language, which is oriented at the systems engineering approach. Thus, supports teams of product developers synthesizing new solutions. The C&CM describes engineering products in terms of *Working Surface Pairs* and *Channel and Support Structures* [16]. Every function of the product resides at a particular set of Working Surface Pairs (WSP) and Channel and Support Structure (CSS), because a function cannot be applied other than through these interfaces. This enables designers to think about abstract functions in a concrete way, because they can picture them at a set of *Working Surface Pairs*. Figure 7 show a C&CM of the pole pruner. In terms of the C&CM approach, descriptions are generated for a particular problem through assigning a set of *Working Surface Pairs* and *Channel and Support Structure* to a specific function and searching for solutions on this clearly assigned level. The C&CM approach then picks and groups elements of the existing description in a new way, exploring in the inherent ambiguity of how elements of a description are grouped.

For example the function of the pole pruner (see Fig. 5) cannot be fulfilled unless WSP0.1 between wood and pole pruner, WSP0.2 between pole pruner and user and the CSS0.1/0.2, which lies in the body of the pole pruner, exist. If one of these elements is not built up correctly, the function *cut off branch* cannot be fulfilled. For example, if somebody tries to cut through a steel pipe, WSP0.1 does not work correctly. The intended quality of the function can only be fulfilled if the user heavily introduces force through WSP0.2.

Reasoning on a lower level of detail it remains to clear why the function cannot be obtained. What effect prevents the sawing through the steel pipe? Is the engine power too low (problem of CSS0.1/0.2), user force too small (problem of WSP0.2) or is the sawing chain at the tip not sharp enough(problem of WSP0.1)? Are there other reasons? To clear such a case remains then in the hands of the designing engineer who might be given the task to create a pole pruner cutting off steel pipes. The following section explains this issue.

3.2 Structuring and Visualizing Objectives of the Development Task with C&CM

In the previous section the hint was given that the reason for the inability to cut through a steel pipe can stem from different locations: sawing tip (WSP0.1), engine power (CSS0.1/0.2), and user force (WSP0.2). Any of these locations contributes to a certain amount to the fulfillment of the function *cut off the branch*, thus serve the objective satisfaction *easy unfixing of a branch*. The objectives of the

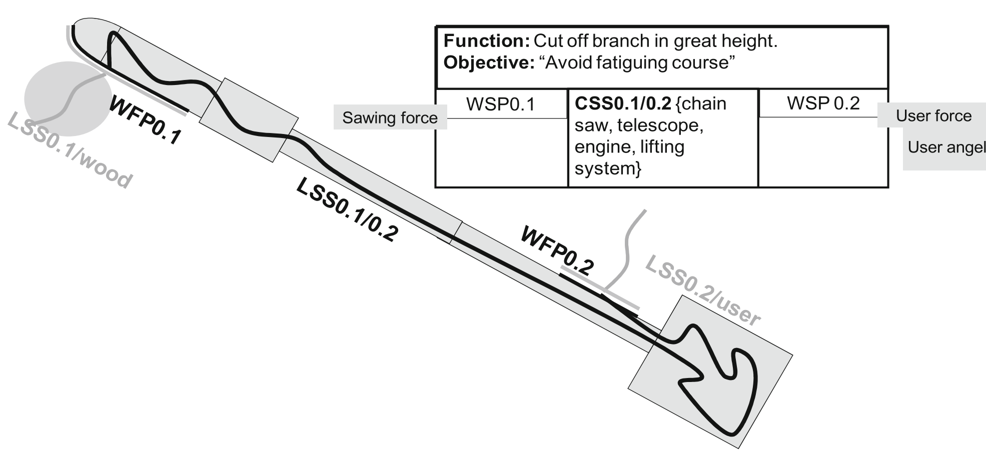

Fig. 7 Function of a pole pruner visualized in C&CM

prospective product development can be structured according to the locations of the WSP and CSS. As objectives and functions can be located in the WSP and CSS of the main function, for each of these elements a new objective can be derived. The system of objectives is specified on a lower rank.

3.2.1 Objectives of the Pole Pruner Evolution

The pole pruner is the product in the system of objects made for the objective "easy unfixing of a branch". The function is determined through the three elements WSP0.1, WSP0.2 and CSS0.1/0.2 (see Fig. 7).

Thus, the objective receives a concrete location on the system of objects. The validation of the pole pruner in relation to the objective "allow for an easy cut through the branch" through validation by means of e.g. extensive testing or feedback from professional users, results in the insight that the quality of the function is not completely satisfied. The working with the pole pruner is exhausting the user too early (After 2 h a normal user needs to stop working).

Through the insight the operation system (designers) changes the system of objectives. A new objective value is defined and further information is saved in order to explain the new objective. *A normal user must be able to work 4 hours overhead with the pole pruner without feeling tired* is defined as the new objective of the product development. In addition the validation of the function results in a distinction of where is the biggest influence on the quality of the function resides: the pole pruner itself, especially the sawing device works very well, but the carrying of the device is circumstantial. From this insight of the validation, subobjectives can be derived according to the locations which were identified as essential for the function of the pole pruner.

Thus, the location with most potential towards the new objective is the user interface at the WSP 0.2 (shown in Fig. 8-right), which is a first starting point for the product

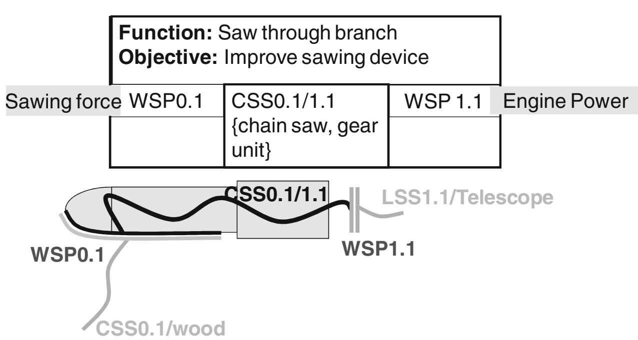

Fig. 8 Function and objective of the user interface

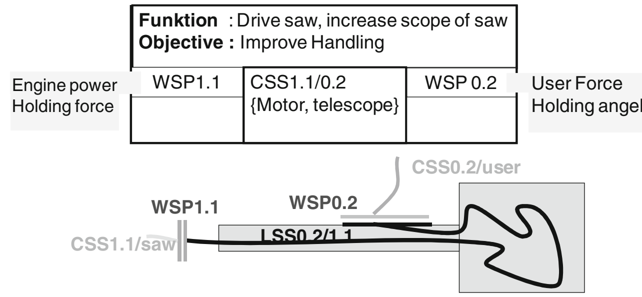

Fig. 9 Function and objectiveof sawing device

development. A team of design engineers can thus be given the objective to improve the sub-function of the user interface. This new objective then is the trigger for the product development, which again in a first step is the hypothetical definition of properties (synthesis) of a system of objects satisfying the new objectives.

The other locations, which are essential for the fulfillment of the function allows the definition of further objectives for the improvement of the pole pruner. But, as the validation of the function bore that the user interface is the most limiting functional location, the improvement of the sawing tip (WSP0.1 in Fig. 9), and the engine and gear (CSS0.1/0.2 in Fig. 9) are subordinated. Thus, a ranking of objective can be undertaken, the process is structured.

3.3 *Complex Structure of Objectives, Derivation of Sub-objectives*

The validation of the pole pruner in relation to the objectives resulted in the derivation of three new objectives. These objectives could then be assigned to a certain WSP and CSS on the system of objects.

The analysis of a single objective resulted in three subobjectives. Yet, the core challenge is to handle a multiplicity of objectives in product development. Within the development of the pole pruner there had to be considered many other functions that were already implemented into the system of objects pole pruner. These functions may not be changed in such a manner that any documented objective might get lost through the implementation of the function. Figure 10 shows an extract from the function and requirements structure of the pole pruner.

The functions and requirements are structured according to the phase of the life cycle (Fig. 10, first line) they appear in. E.g. recycling capabilities are derived from the objectives that the *system must recyclable after use*. Also in the sequence *operation* (Fig. 8, second line, left) there is pointed out the functional structure of the combustion engine. The know how to build these combustion engines is a

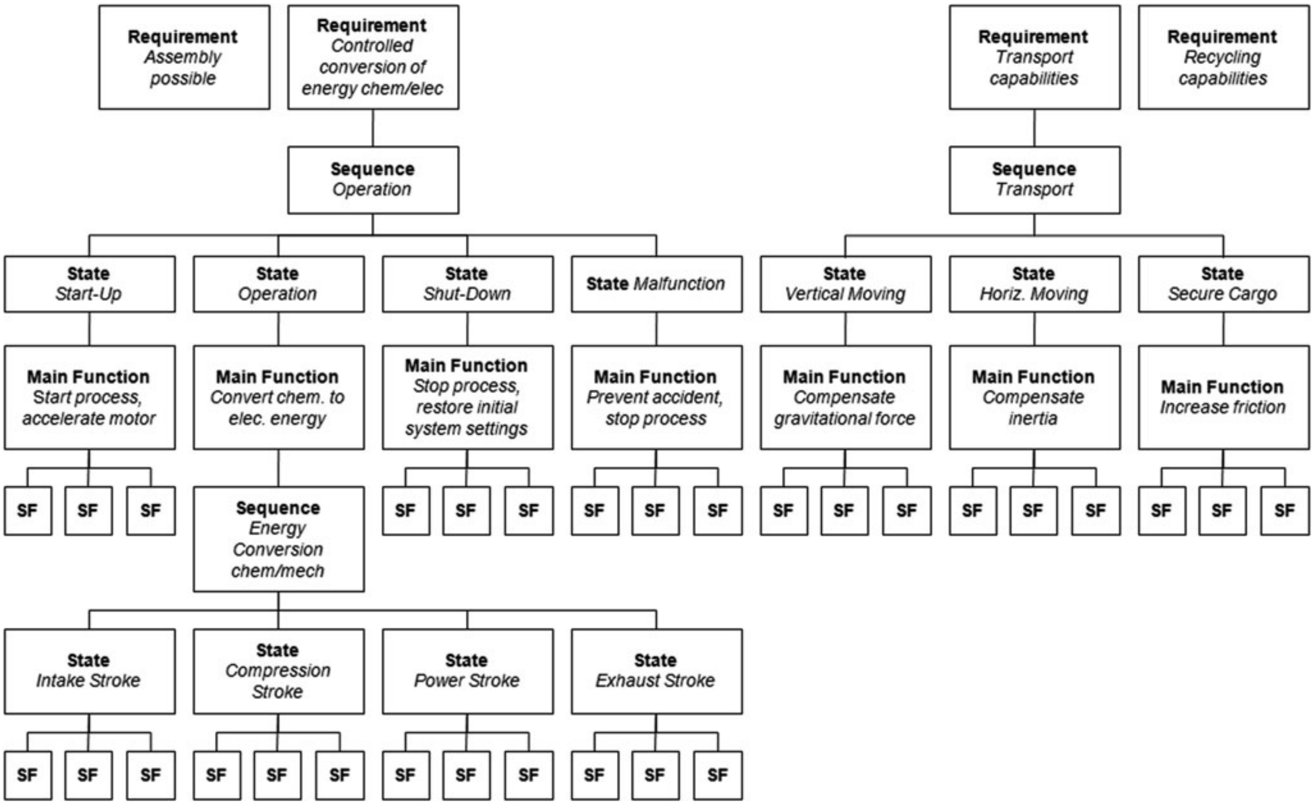

Fig. 10 Structure of explicit objectives, requirements and functions

core competency of the company developing the pole pruner. However, an objective is to use these combustion engines in as many products of the company as possible, because alone the application of such an engine bears a huge advantage in competition.

3.4 Current Research

Research on the Contact and Channel Model has not yet accomplished the implementation of a complete system of objectives of e.g. the complete pole pruner. This chapter introduces the idea of structuring the objectives of product development by means of the C&CM.

The C&CM has proven in many projects (e.g. [16]) that it performs to integrate abstract functional descriptions of product development by giving a concrete location to the abstract functions and thus reduces the risk of misleading of the process. Research on the Contact and Channel Model focuses on two aspects: First of all, a key to spread the method more widely is to find the adequate mechanisms to anchor the way of thinking in the heads of designing engineers. Therefore the application of the C&CM is surveyed empirically in industrial projects. A strong focus in the run of these projects is the handling, cognition and articulation of abstract functional as well as objective representations in design processes.

The second stream is the implementation of the model into a computer system. As argued throughout the paper only isolated applications exist and are sparely applied. First approaches to implement the C&CM into a computer tool are ongoing [17].

4 Conclusion

C&CM helps structuring objectives in product development. Objectives are given concrete location on physical artifacts, on products and on object in the system of objects. Thus, objectives can remain transparent throughout the development process. The control of the development process can here with be conducted more efficiently. Detours and trial and error processes can be avoided or conducted with less effort as all involved designer gain a better understanding of the complex structure of the multiplicity of the objectives.

The approach presented in this chapter contributes to unify the research on the management of design processes and design methodology by means of the system of objectives, system of objects and operation system. The management of design processes is oriented at the results of the product development process, thus deals with abstract objectives. The course of reaching the result is rather neglected. On the other hand the C&CM is originated in the design methodology corner of research in design engineering. Design methodology rather focuses on the "how" to reach the objectives. Objectives in design methodology are assumed as definite cornerstones. Thus, the approach presented in this chapter contributes to bridge the gap between management and methodology of engineering design.

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Collaborative Aspects in Global Product Development

Integrating Product Model and Whiteboard to Ease Collaborative Work in Global Product Development

H. Vu-Thi, P. Marin, and F. Noël

Abstract Product development was deeply modified by globalisation. New practises to ease remote collaborative work are expected. Many methods and tools were developed for this objective in a fragmented vision depending of the usage contexts. The computer supported cooperative work (CSCW) community defined tools dedicated to generic collaboration without specialisation about a specific business. Under this classification, whiteboards are dedicated to synchronous remote work around unstructured sketches. On another point of view the design community developed new shared models for structured information about the product. This chapter proposes the integration of both in order to create whiteboards dedicated to technical business activities.

Keywords Collaboration · Design · Shared whiteboard · Product model

1 Introduction

Product development is a specific collaborative work activity. Its increasing complexity expects collaboration of many designers with their own specific role. With globalisation the management of collaboration becomes a major bottleneck for companies. Solution may take many forms from managing high level coordination of companies, down to facilitating the every day technical work of two engineers working on remote location. In the later case, the literature defines several research visions: (1) the CSCW vision mainly working about the collaborative work for no specific contexts and (2) some business oriented works where usually the formalisation of information exchanges between engineers is a major issue.

In this chapter, the authors propose a bridge between the two visions by integrating a whiteboard, which is a paradigm issued from the CSCW community with a Product model which is a product development oriented paradigm. This integration is not so natural since a whiteboard is usually referred as a tool for unstructured exchanges while product models are mainly dedicated to structure information shared by engineers. However this integration could bring a right balance between the various structuring levels expected by product design and product development activities.

The paper is divided as follow. In a first part the whiteboard concept and advantages are described, and a specific implementation of a whiteboard which will be used for prototyping our proposal is also presented. Then, the product model concept and various existing instances are described, and a model driven engineering environment is described, that may be used to quickly adapt and share a new product model. In a third part, the integration of both is proposed, together with the new functions that should be provided in a whiteboard in connection with a product model.

2 Whiteboards

2.1 *Whiteboards in CSCW Approach*

A shared whiteboard makes it possible to several distant people to build a drawing or a diagram in collaboration. Each participant has on his screen a window containing a common drawing space. Each traced feature or any other modification carried out by any participant is reflected at once on all the other stations.

In the now well-known space-time classification matrix for collaboration situations and related collaboration tools [1], a shared whiteboard clearly belongs to the "same time/different places" collaboration mode (Table 1).

Several authors [2–4] pointed out the importance of graphic communication in product design activities. We could also observe in a variety of situations, from industrial

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Table 1 Space-time collaboration tools classification

	One meeting site (same place)	Multiple meeting sites (different places)
Synchronous communication (same time)	**Face to face interactions** – Public computer display – Group decision support tools – . . .	**Remote interactions** – Application sharing – Desktop conferencing – Video conferencing – Shared whiteboard – . . .
Asynchronous communication (different time)	**Ongoing tasks** – Team rooms – Project management – Shared bookcase – Product model repository – . . .	**Communication and coordination** – e-mail – Structured messaging systems – Meeting scheduler – Product model repository – . . .

project reviews or academic design situations, in co-located meetings like in distant collaboration situations [5], that graphical support is an issue in most of engineering exchanges, in different phases of a design project.

Recently observed situations relate to two sessions (‘08 and ‘09) of “the 24 h of innovation” contest organised by Estia [http://www.24 h.estia.fr/] where a few design teams have been involved in a geographically distributed way. It appears that, in order to keep maximum mutual awareness from one site to the others, in addition to a videoconference flow, a graphic space (whiteboard with graphic or sometime hand-written notes) was shared during more than 80% of the duration of the project. In the last session of the contest, the two observed teams were distributed in 2 or 3 sites, with the main groups (almost 10 people for each team) located in Grenoble, and one or two members situated in Estia (for the communication with the organisation staff and the exchanges with the clients of the projects) and also another location in France. Both teams have been provided with an interactive whiteboard device and application sharing software.

Both teams used intensively these tools, and depending on the topic of the project, the first team mainly shared ideas and concepts through textual notes and sometimes annotated pictures (Fig. 1), while the second team shared lots of graphic information in form of technical sketches (Fig. 2).

From these observations and from other studies developed in [5], it is assumed in this chapter that for geographically distributed design teams, the availability of rich graphic information exchange is an issue for efficient technical design communication.

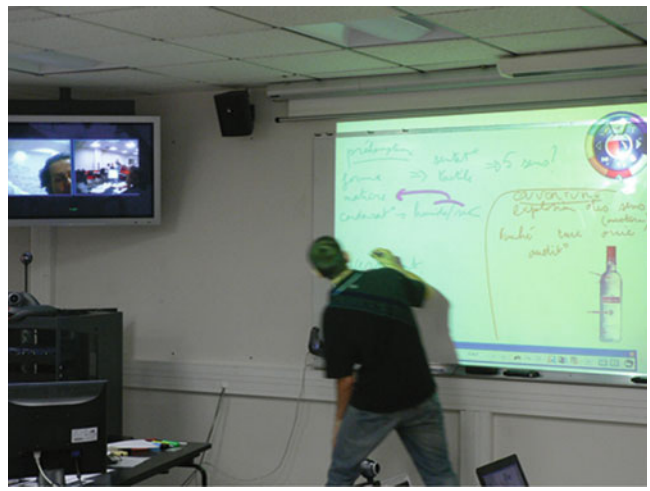

Fig. 1 Sharing information and line of argument through interactive whiteboard and Polycom videoconference

2.2 Existing Commercial Implementation

Apart of free-hand sketching, distant collaboration environments usually provide a shared whiteboard. Some of them are cited in Table 2.

Some are dedicated to project review (e.g. Centra eMeeting. . .) with main features oriented to presentation management with predefined meeting agenda and support documents. Others are specifically efficient for application sharing, even with OpenGL CAD software (e.g. Arel or SameTime. . .). But it appears that the shared whiteboards of these applications have simple features, dedicated to at most redlining activities around shared PowerPoint-like presentations.

Some “online whiteboards” (OWB) are also now available on the Internet, like Scriblink [6], Groupboard [7], Twiddla [8] or Dabbleboard [9].

Among those, Scriblink and Twiddla feature an online equation editor [http://www.sitmo.com/latex/] that may be useful for engineering collaboration. DabbleBoard features automatic shape detection, and a set of thematic drawings that could also be useful to make fast and clean drawings in engineering communication contexts.

Fig. 2 Sharing technical sketches through interactive whiteboard for the co-located, and Arel Spotlight application sharing for remote collaborators

Table 2 Some collaborative environments providing a shared whiteboard facility

Software	Enterprise
NetMeeting	Microsoft
SGImeeting	SGI
In Person	SGI
Meeting Point	VCON
Centra eMeeting	IVCI
SameTime	Lotus
Sun Forum	Sun
Visual Conference	HP
Arel Spotlight	Arel Communications & Software
Marratech	Marratech AB

Fig. 3 Shared whiteboard in lotus sametime

2.3 Whiteboard Usage for Collaborative Design Activities, Advantages, Limits and New Features

Through educational context for several years, we could analyse the usage of collaborative whiteboards in engineering design projects, where three to five engineering students of different competencies were involved over a period of 6–8 weeks and five or six synchronous collaborative sessions, 2–3 h each. Students in these workshops have been put in various collaboration situations, distant or co-located, for various purposes from brainstorming to project review through technical direct exchanges and argumentation. The observation of these situations has been presented in [10]. Collaboration environments that were manipulated in these projects are Microsoft NetMeeting, Lotus Sametime (Fig. 3), Arel Spotlight, MindManager in conference mode, all with shared graphic facilities.

The use of these software tools led to the assessment that they miss various functionalities. Graphic entities available (in a few words: line, rectangle, ellipse, and arrow) are well adapted for redlining on a shared 2D intermediary object, but not suited to make a technical sketch, diagram, table, equation, etc. needed to explain or argue, or simply exchange ideas in an engineering project dialog.

As Törlind and Larsson pointed out in [11], informal communication and awareness are also of great significance for

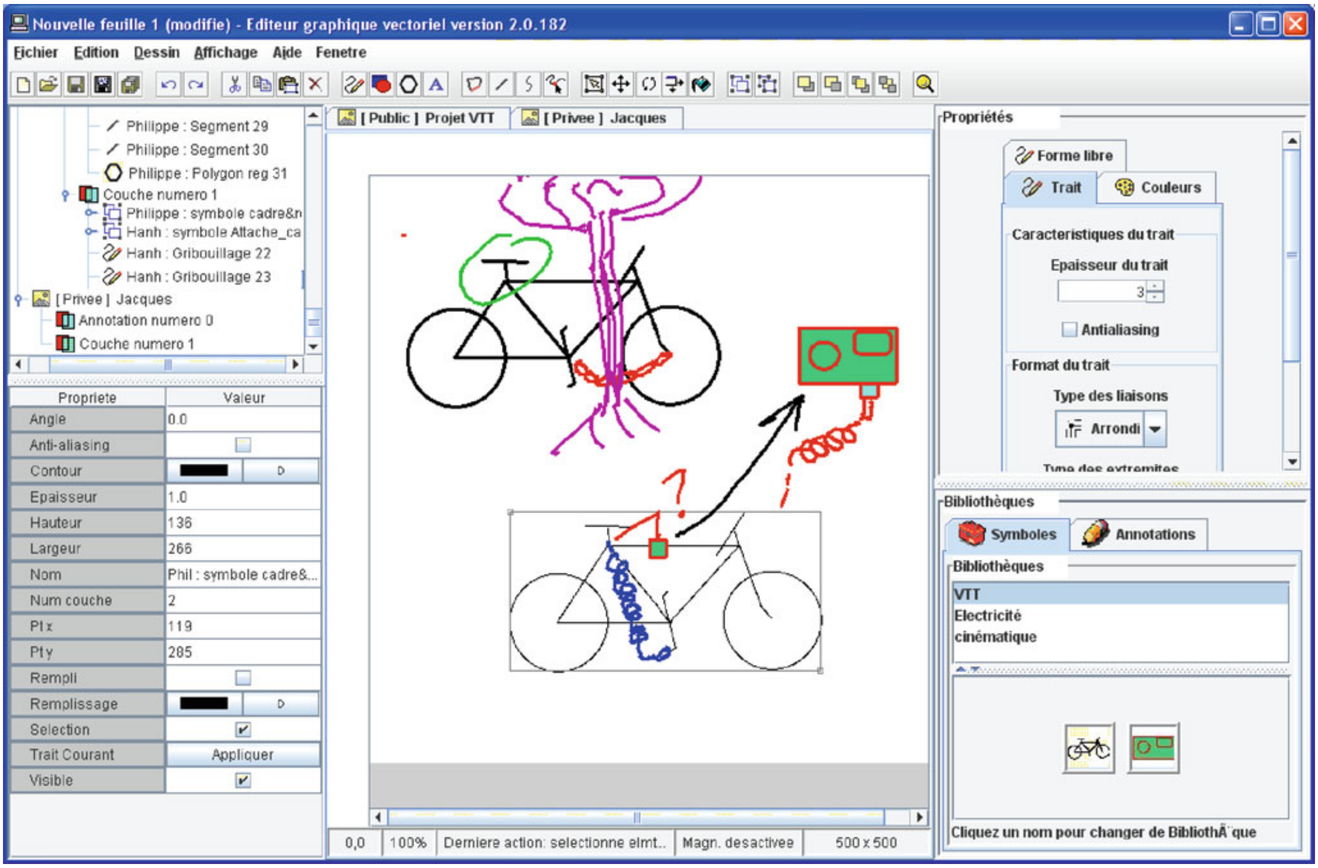

Fig. 4 A view of an enhanced shared whiteboard

successful group collaboration. Thus apart from previous technical communication aspects, commercial shared whiteboards also show a certain lack of social communication and awareness features.

We thus proposed some further software developments in order to improve a collaborative whiteboard dedicated to technical design. Among the proposed enrichments, there are graphical ones (ability of manipulation of diagrams, equations, tables, discipline symbols libraries, etc.) and others concerning social or awareness aspects (shared legend, identified pointers, private vs public spaces, page changing synchronization, redlining eventually separated from the main intermediary object, structured and multi-users hierarchical annotation, etc.). Figure 4 shows a view of the current version of this whiteboard, where a part of these new features are already available.

It is proposed in Sect. 4 of this chapter to go further in these enhancements, with the first developments of a new paradigm that lead to connect the shared whiteboard used in synchronous meetings to the product model database, and to allow designers to access shared product parameters through this graphic interface.

3 Product Modelling

3.1 Product Modelling Paradigm

Product model paradigm was initiated in 1994 by Tichkiewitch [12], Tichkiewitch and Chapa Kasusky [13] and Krause et al. [14], and then formalised by Roucoules and Tichkiewitch [15] in 2000. The main idea remains to define a space for sharing information about a product. Engineers from various skills and know-how require a space to share information rather than to exchange it. Indeed classical exchange is based on standards which remains limited to geometric information (relevant for CAD geometry) and which is a source of information lost and duplication.

Then several research directions were to be undertaken:

1. To extend capacities of exchange formats: Standard For The Exchange of Product Model Data (STEP) [16] was the main development in this direction. Every points of product development is analysed and structured through the EXPRESS language in order to avoid

misunderstanding of the developed schemes. It must be noted that STEP was also designed as a unified model and should have been used as a shared product model. However STEP remains mainly used for exchange and intents to use it as a unified model are rare [17]. Only few commercial software was designed to be compatible with the STEP standards.

2. To propose standard application protocol interfaces (APIs): to open access to business application the development of more or less standard access protocols were proposed. Main commercial use provides associativity between business oriented application with CAD (Computer-aided design () geometric modellers. The CAD geometric model is used as the reference for product modelling and associativity is a way to ensure compatibility of the business model with this reference. An update function is classically developed: whenever the CAD model is edited, the business model is recomputed to reflect the new geometric reference. Usually commercial APIs are associated with every commercial software. The standard "CAD services" API [18] was developed by OMG (Object Management Group) (www.omg.org) but was not clearly adopted by the commercial offers.
3. To develop "Product Data Management" system (PDMs): the CAD software providers understood that CAD geometric information was not enough as a reference model. PDMs were developed as shared repository of a hierarchical description of the product. The product is decomposed into a hierarchy of articles which can be associated files. The unit of information remains files issued from various CAD and non CAD software. The access to fine information as geometric parameters or density of a material is not a level of detail which can be easily accessed.
4. To develop product models that could be shared by every business views. Formalising cognitive analysis of engineers Gero proposes the FBS model [19] standing for Function-Behaviour-Structure. He analyses the possible paths between definitions of product function, product behaviours and product structures. FBS paradigm will be used again in many product model approaches. Indeed FBS relates some older systemic approaches where a system may be defined through three perspectives: (1) what the system is: its structure (2) what is it for: its function and (3) How it evolves: its behaviour.
   Whatever the chosen direction, the main goal is to share information. Engineers expect:
5. To get up to date information adapted to his/her own point of view.

   - To avoid misunderstanding and duplication of information which are sources of incoherency for the overall project.
   - To share information about the product at various levels of detail. The need to share fine parameters depends on the context of activity. In some cases the vertex of a NURBS (Non-Uniform Rational Basis Splines) complex surface may be an objet of collaboration while in most cases parameters are at a higher level of abstraction.

3.2 State of the Art in Product Modelling

The development of product models remains an academic attempt to define a generic representation of products. FBS paradigms are used in various models. Literature provides several models with no decisive criteria to adopt one rather than another one. Roucoules proposed the Interface Entity Constraint [20] model. Constraints stand for functions and in some cases for behaviour. The IPPOP (Integration of Product – Process – Organisation for engineering Performance improvement) project proposed the PPO (Product Process Organisation) model [20] creating links between product model, development process and organisation model: the product part of the PPO model includes Function, Behaviour and Structure entities and provides links between these entities. An open list of parameters may be associated with every entity to reflect the attributes expected by every business actor. The FBS-PPRE model extends also the FBS model to product process resource and external events (PPRE: Processes, Products, Resources, External)…. The NIST (National Institute of Standards and Technology) developed the Core Product Model [21]. The CPM uses a Model Driven Engineering Approach by defining a high level conceptual model mainly based on a representation of Functions, Behaviours and Structures paradigms. This abstract model must be developed by inheritance for every specific business view. Then the interactions between business views are formalised by referring to the upper abstract view.

Other models are still developed. Gurumoorthy developed the DIFF (Domain Independent Form Feature) model [22] to ensure interoperability with the feature tree of a CAD system. If paradigms are less generic than in a FBS oriented model, it provides an obvious efficiency for current interaction between existing applications which remain leaded by CAD concepts. The OMG also proposed now SYSML [23]. SYSML stands for System Modelling language. It is a dialect of UML (Unified Modelling Language) which provides graphic representations of system perspectives. SYSML was specialised for manufactured products description. However, as UML, this language remains unknown from engineers (indeed UML is mainly used by computer scientist) and its deployment may be hard. Indeed UML like models are pretty good for high level abstraction. The description of a class diagram remains visible on single sheets. However, an object diagram instantiating such a class diagram is quickly impossible to represent on a 2D sheet whenever the system complexity increases. Since the role of product development engineers remains to develop product representation, to use object diagram for this major task will remain too complex.

3.3 A Simplified Product Model

With the previous state of the art, it is hard to identify the right product model. It is context dependent since none existing models demonstrate their full generality. We can imagine simpler model. A table of parameters may be seen as a very simple product model as soon as this table is shared and agreed by every engineer. To ease agreement more semantic may be expected by associating parameters to almost a product structure.

Figure 5 proposes a UML diagram class of such a model. It demonstrates that we can develop a new product model very quickly and with few concepts. A structure component may be decomposed into sub structure components. This is the role of the association linking the class "Structure component" with itself. Thus we describe a classical hierarchy of components. Every component may be associated with a set of parameters which are specialised with various value types.

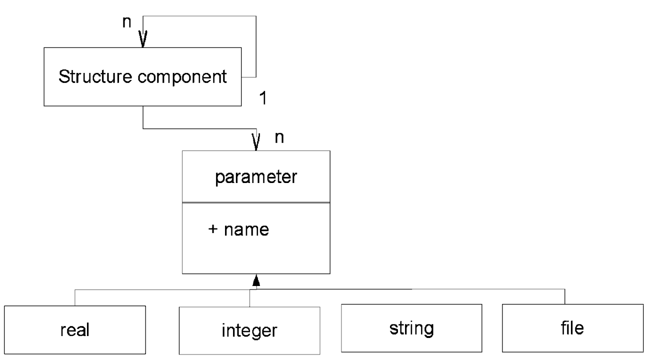

Fig. 5 A simple product model

3.4 An Environment to Manage a Product Model

Face to the amount of potential product models we developed a MDE (Modelling Development Environment) environment to manage various type of product models. This environment, named GAM, allows through a graphic user interface to define a specific product model and to instantiate it to represent specific objects.

Figure 6 describe the product model issued from the previous section described in the GAM environment. The classes with their specific attributes were defined. The inheritance is also defined but not visible on the graphic user interface. Figure 7 shows in the same environment the basic description of a specific product described with the product model.

A bicycle was defined by a structure component named "TheBicycle" and currently spitted into two wheels and one frame. The "TheBicycle" and "Frame" entities share a same parameter named "Size" which defines a real value.

The GAM environment shares the product model and its instantiations over a web connection. Even if this product model and its instantiation are really simple it expected only 10 min to be formalised and shared with the GAM environment. More complex product models were integrated and can be used thanks to this environment. It can be noted that this system makes the product model and the representation evaluative. They can be adapted on the fly of design to reflect any new context of work. It can be also noted that the graphic user interface does not suit the ergonomics that should be expected by engineers.

4 Integrating Whiteboard with a Product Model

In the space-time classification matrix, whiteboard and product model do not relate to the same collaboration contexts. On one hand whiteboard relates to same time/different places, while on the other hand product model is dedicated to store product data in the long term, to be accessed at any time, and indeed relates to different time, whatever the places are.

Nevertheless, we state with other authors [24, 25] that various communication modes are required in the course of a design project, and that the timeline is made of asynchronous phases converging to synchronisation ones.

In terms of information manipulated, there is a continuum in communication situations together with information flows: data, knowledge or information involved in synchronous meetings must be stored and reused in asynchronous activities, and on the other hand, synchronous meetings are fed by data and information provided by asynchronous work.

4.1 Whiteboard as a Graphic User Interface for Product Modelling

Whiteboard remains dedicated to informal sketches. Whenever it is used for product development activities, the information shared with the whiteboard will mainly concern the product definition. The sketch can then be analysed as a representation of the product which will register information about its functions, its structure and its behaviours. The whiteboard thus becomes a graphic user interface for product modelling. A step will be passed when the sketch will be connected to a structured product model.

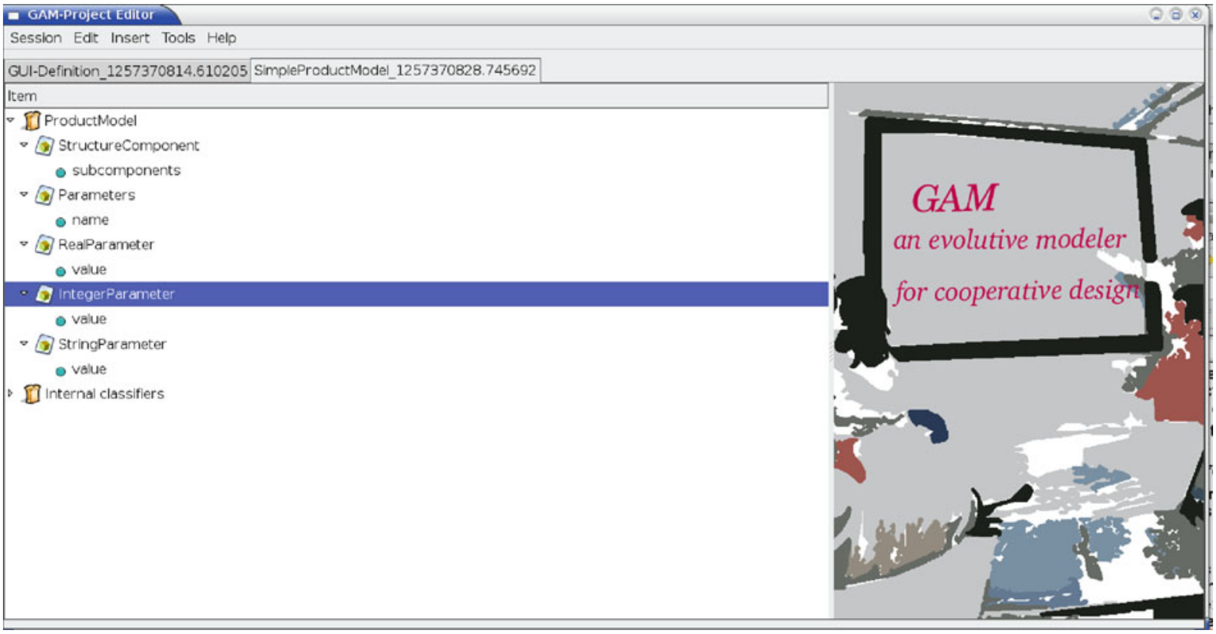

Fig. 6 A simple product model in GAM environment

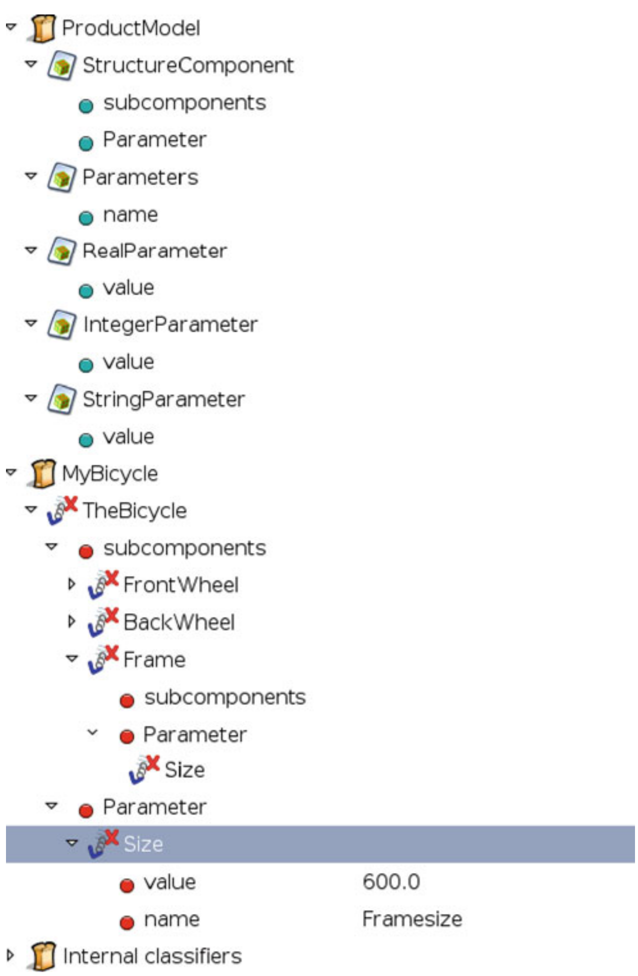

Fig. 7 A shared representation of a product

On one hand the whiteboard will provide more flexibility to engineers to enter information into the product model. The information is defined at the right abstraction level since engineers will choose respect to the current design context which parameters may be defined. A sketch item is associated with any entity of the product model. It creates a narrow link between the two representations.

On the other hand, a product model may also be used to register a library of standard products. A 2D sketch or an image may be associated to these products. To access the product model will provide to the whiteboard the access to structures information associated with the symbol which is shared with a 2D sketch or image.

The whiteboard becomes a tool for cognitive synchronisation about what is shared within the product model. Without avoiding it, it could limit duplication and incoherency of information since the abstract level of discussion remains on real collaborative data.

4.2 Which Kind of Product Model May Be Connected?

Any kind of product model may be associated with a whiteboard. Nevertheless, it appears that light product models (with little number of entities) may be more adapted for collaboration through a whiteboard. As soon as the number of concepts increases the ergonomics of the whiteboard will be also increased. The whiteboard must remain a tool for free and quick expression. It will be necessary to make ergonomic experiments by increasing the complexity of the product model to demonstrate when engineers stop to use the whiteboard.

This kind of ergonomic experiments will define an efficient measure of the capacity of the product model to be human processed. A STEP models which works at a very fine level of product definition will be clearly rejected by this test. Connecting a whiteboard with the DIFF model will be also hard since the DIFF concepts are not usual for collaboration. It will be interesting to check the efficiency of other models like PPO, FBS-PPRE, CPM or also SYSML.

4.3 Sharing a Sketch with Various Points of View

Some observations of inter-discipline work [26] have shown that not only the parameters but also the related concepts manipulated by an engineer are generally not the same as those manipulated by a colleague of another discipline. This work pointed out the need of informal communication among people involved in the design process, so that a common ground is built and shared in the project team. This common knowledge in the project context includes a certain level of awareness and understanding of the concepts manipulated in the different professional worlds [27] involved.

This led [28] to propose the development of a collaborative environment to share professional concepts and related parameters (CoDISS: Cooperative data & information sharing system). This environment includes a translation system that offers the ability to link parameters from one model to parameters from another model, and to build on the fly translation rules between these sets of parameters. Translation may involve more or less simple mathematical relations that link several parameters, unit changes, acceptable variation range, modification cost, etc. This additional information about product parameters is clearly of importance for robustness of the design process, and has to be shared among design actors.

The translation module (Fig. 8) makes, for each designer, a link between his personal view on the product, and the common view available in the shared product model.

The integration of this parameter sharing and multi-view translation aspect of CoDISS in the whiteboard will provide designers with a well suited collaboration tool that will allow them to exchange and synchronise about these shared design parameters.

A further step in this multi-view paradigm will then be to consider not only the variety of parameters used by designers and their inter-relations, but also the graphic multi-representation of concepts according to discipline points of view. Based on the symbol libraries already included in the whiteboard software, it is indeed possible to build concepts items that have different graphic representations according to the actor's discipline, and to adapt the sketch to the various points of view.

4.4 A Usage Scenario

Imagine a situation where a team of engineers, together with marketing people and technical staff working on the design

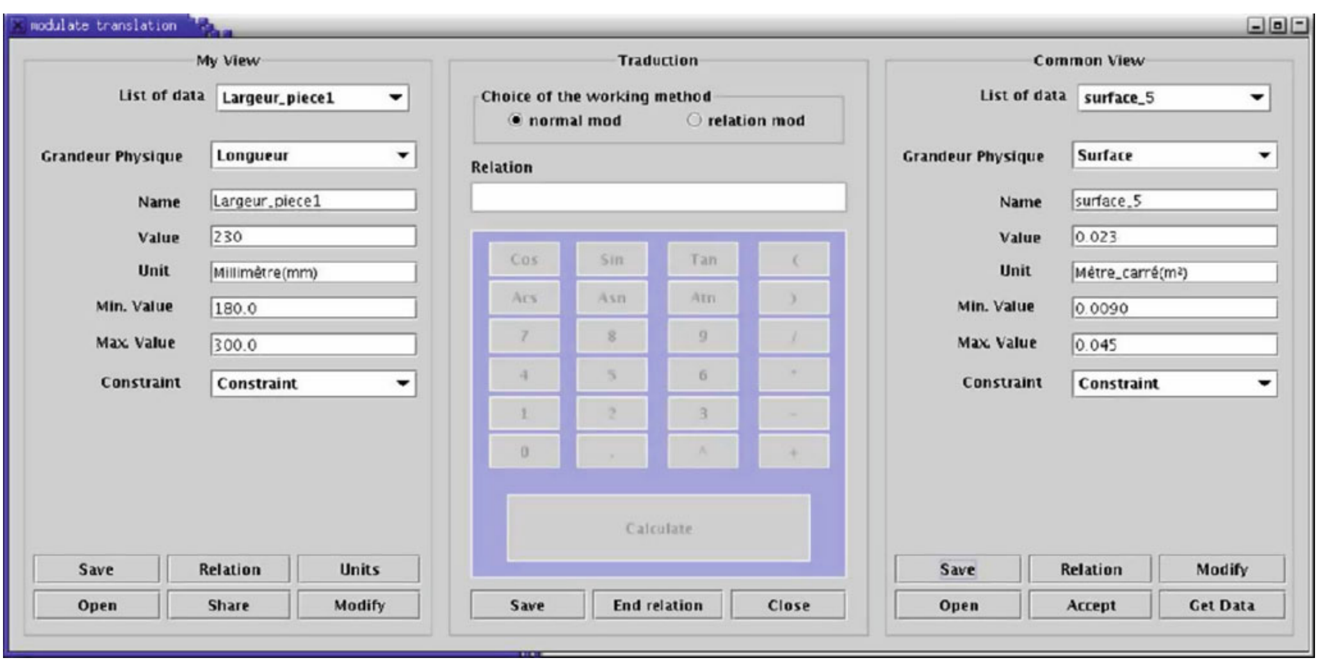

Fig. 8 The multi-view translation module of CoDISS

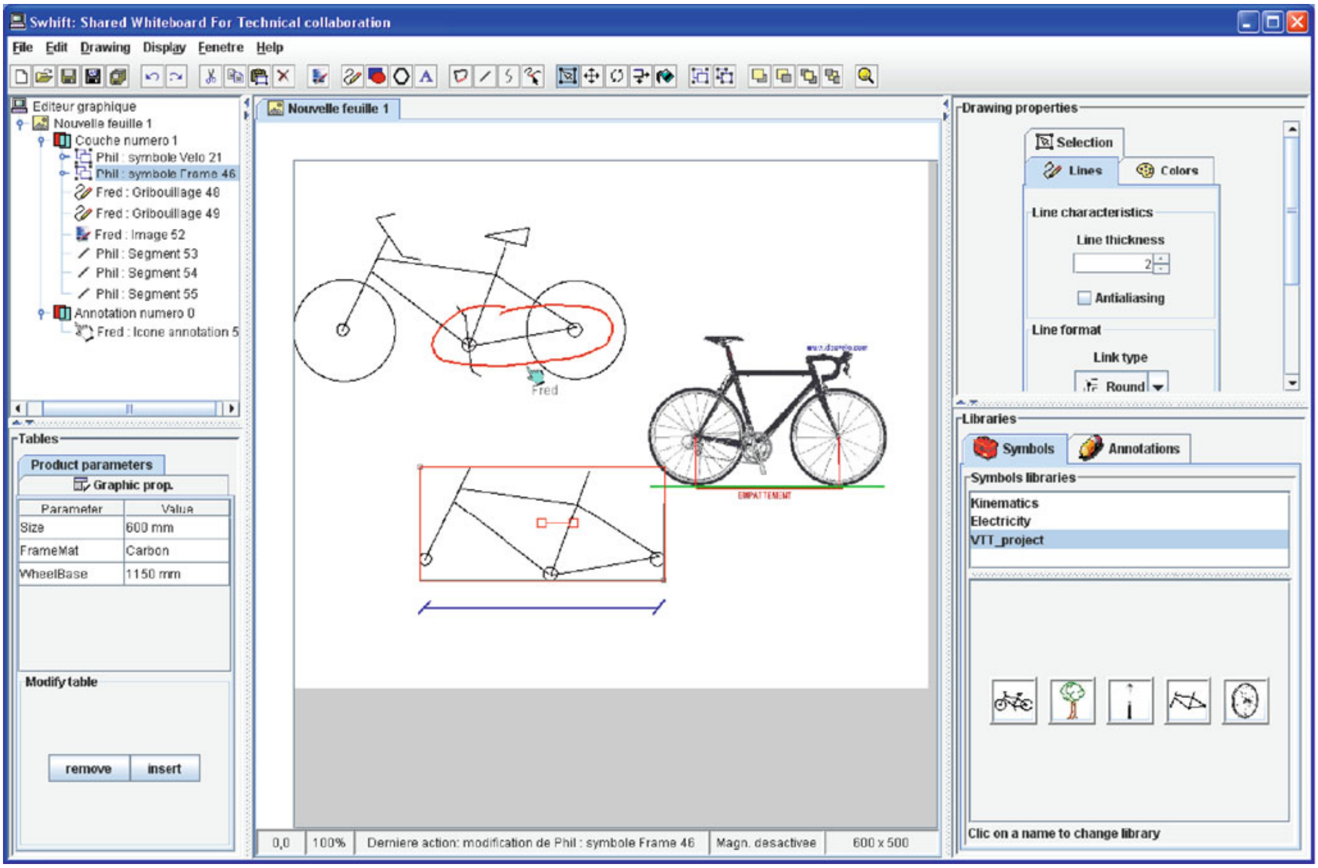

Fig. 9 Links to parameters associated with the symbol "Frame" which is selected in the whiteboard

of a bicycle, are involved in a synchronous meeting where they have to discuss and exchange detailed information about technical constraints related to some features of the frame.

By coupling some functionalities of the new whiteboard described in Sect. 3 and its connection to the simple product model proposed in Sect. 4, it becomes possible for every participant in the meeting to access shared parameters through associated graphic items (either a drawing just made in the flow of the dialog or an already defined item in the project symbols library). Figure 9 shows such a scenario.

5 Conclusion

From the development, on one hand, of an enhanced shared whiteboard dedicated to technical collaboration in product design, and on the other hand of a simple product model (based on the generic environment GAM), the main idea of this chapter is to create a link between graphic items manipulated in the collaborative whiteboard and items shared in the product model. This link is materialized by shared product parameters. It should be noticed that this also creates a formal link between synchronous and asynchronous collaboration phases.

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Multi-user Collaborative Design Tools for Use in Product Development

R.G.J. Damgrave and D. Lutters

Abstract This chapter describes the advantages of using multi-user collaborative design tools within product development, and what it takes to simultaneously work with multiple users on one virtual tool. Initially, it is explained why collaboration is essential during product development and how current virtual tools fail at facilitating and stimulating it. An introduction is given to multi-touch interfaces that offer the opportunity to create multi-user collaborative design tools, followed by an explanation of the most important challenges in creating multi-user virtual design tools.

Keywords Collaborative design · Multi-touch user interfaces · Graphical user interfaces

1 Introduction

Working in a team environment is often one of the key issues in the development of new or renewed products. The need to work with a team of people can have different causes, but will eventually result in the division of work according to the background and field of expertise of the team members. The combination of those different fields of expertise is the key element for success in a product development team. With the use of information technology, companies try to facilitate the collaboration and communication between people. Often, this results in individual work on a computer, where all the communication between the team members is done in a virtual world. This often lacks the possibilities to have a face-to-face communication with colleagues.

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2 Collaborative Work

2.1 Aim

The average product development cycle brings together the work of many different designers, engineers and other stakeholders. Each of them is an expert in his respective field of expertise, and as such has a valuable contribution to the overall development cycle. To employ that expertise to its fullest extent, the interaction between all stakeholders involved should be as effective and efficient as possible. This interaction can realise synergy in the development cycle, for example because pitfalls can better be foreseen. Moreover, the quality of the resulting product is likely to increase as well.

The interaction between the stakeholders of the product development cycle can be supported in many different ways, based on a variety of working methods and (computer based) tools. The overall term for the contact between the stakeholders is (computer supported) collaborative work, or CSCW.

2.2 Definition

In general, computer supported collaborative work is defined as the activities that combine the understanding of the way people work in groups with the enabling technologies of computer networking, and associated hardware, software, services and techniques.

The successful application of new information technology (IT) to support cooperative work in an organization depends not only on characteristics of the technology but also on characteristics of the organization, such as organizational structure or organizational culture, management strategy, and on the characteristics of end-users and their motivation, as well as cognitive factors. Consequently, the introduction of a sheer set of tool will definitely not vouch for adequate

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synthesis between stakeholders. This is all the more true in realizing that collaborative work may be considered to be required in four different circumstances:

- Same time/same place
- Same time/different place
- Different time/same place
- Different time/different place

2.3 Implications

Each of these circumstances dictates different interaction types between the stakeholders. For example, in addressing collaborative work at different time, the focus will be on the registration of generated information and making it available to others. Tools for the support of this type of operation range from extremely simple solutions, like white-boards to leave messages behind, to complex full-featured knowledge management systems. In any case, these systems boil down to off-line communication, for which a wealth of solutions is already available.

Considerably less out-of-the-box solutions are available for "same time" situations. The existing solutions either realise generic communication possibilities for stakeholders (like chat or video conferencing) or facilitate decision making processes. Another category of supporting tools aims at improving the one-way communication in the form of e.g. presentation tools. Consequently, especially in the situation where stakeholders could concurrently and conjointly realise the most added value, the tools are rather generic, superficial and one-directional in nature.

To further investigate the circumstances that allow for adequate collaborative work, it is interesting to take into account seven norms that address the circumstances that allow people to conjointly realise added value; either at the same place or remotely. The norms themselves are not the "laws" of collaborative work, they, however, give some additional perspectives to assess the way in which collaborative work is organised.

Pausing: A pause in discussions enables for interaction. It dignifies contributions and implicitly encourages future participation. Pausing enhances discussion and greatly increases the quality of decision making.

Paraphrasing: The paraphrase maintains the intention and the accurate meaning of what has just been said while using different words and phrases. The paraphrase helps members of a team to hear and understand each other as they evaluate data and formulate decisions.

Probing: Probing seeks to clarify something that is not yet fully understood. More information may be required or a term may need to be more fully defined. Clarifying questions can be either specific or open-ended, depending upon the circumstances. Probes increase the clarity and precision of a group's thinking.

Putting forward ideas: Ideas are the heart of a meaningful discussion. Groups must be comfortable to process information by analysing, comparing, predicting, applying or drawing causal relationships.

Paying attention to self and others: Collaborative work is facilitated when each team member is explicitly conscious of self and others; not only aware of what is said, but also how it is said and how others are responding to it.

Presuming positive presuppositions: Assume that other members of the team are acting from positive and constructive intentions (however much disagreement may exist).

Pursuing a balance between advocacy and inquiry: Inquiry provides for better understanding. Advocacy leads to decision making. Both are necessary components of collaborative work. One of the common mistakes that collaborative teams may make is to bring premature closure to problem identification (inquiry for understanding) and rush into problem resolution (advocacy for a specific remedy or solution).

2.4 Scenario

Bringing together the currently available tools for collaborative work and the seven norms mentioned above, crudely uncovers the gap between the technology of the tools and the use intent of the different stakeholders. For example, the organisational culture in a company (or group of companies) may definitely clash with hierarchical ways of working that are embedded in many tools. Especially "same-time" solutions seem to lack adequate possibilities as the "etiquette" of the seven norms is concerned.

Therefore, considerable improvements to conjoint product development and the required synthesis can be achieved by better facilitating the way in which stakeholders can interact in real-time situations. Independent of their location, they should be supported in collectively working towards engendering the best possible product. This implies that no prevalent hierarchy needs to be present, the tools are equally accessible for everyone and the underlying technology does not hamper the process. The latter suggests that the used hard- and software is not only used for decision making, but also for creating variants and assessing alternatives while continuously employing everybody's input in the appropriate manner. In other words, focus has to shift from "deciding together" to "realising together".

This calls for a situation where multiple stakeholders can work together in a virtual setting. This virtual setting (that can be anything from a shared notepad to a full-blown 3D environment) brings a shared perspective to all stakeholders involved. This perspective allows for the integration of the different fields of expertise, while doing justice to all the independent viewpoints. Based on effective solutions for a virtual setting, team members can more easily incorporate the norms for collaborative work in their development projects.

3 Tools

3.1 Multi-User Graphical User Interface

User interfaces are the link between computer systems and human input; their aim is to show the user the opportunities and choices available for interacting with the system (at that specific time). Currently available graphical user interfaces (GUI) from computer supported collaborative work tools are generally based on a single user use scenario. Therefore the interaction methods with these systems are difficult, or even impossible, to implement in a team setting. To implement future CSCW tools, multi-user graphical user interfaces should be in line with the possibilities of the tool. A multi-user GUI must allow for and facilitate simultaneous input from multiple users. A non-predefined number of people must be able to interact with the system and work on both individual and collaborative tasks within the same GUI, independent of their physical location. The main difference between a single-user and multi-user GUI is that the chosen virtual tool is not only task specific but task and user specific in case of multi-user interaction. Moreover, a multi-user GUI does not rely on a hierarchy in the team setting, since the arrangement of users can vary during the process.

3.2 Available Tools

During collaborative work sessions, several tools are used to stimulate and facilitate the collaboration between the team members. Looking at the current tools, the projector is one of the most commonly used. It is used to visualize the information presented by one person, where the discussion the presentation can generate is the collaborative aspect. A projector itself does not provoke collaboration. Moreover, the projected image inherently imposes one-way communication on the participants, who therefore do not have equivalent roles in the meeting. Also tools like e-mail and shared documents can facilitate specific needs for collaboration, whereby the main goal is to spread the documented information among a group of persons. An example of a tool which is actively involved in a collaborative session is the interactive whiteboard. This extension to the projection screen allows the users to virtually draw on the screen using special markers. The advantage of using a virtual whiteboard is the possibility to digitally archive the material and (offline) spread it among the involved people. Another advantage is the option to draw as an overlay on existing images, where the presented information can be used as staring point.

Allowing multiple persons to interact simultaneously with computer systems foremost requires the system to allow multiple inputs. Technologies like multi-touch screens make it possible to recognize multiple inputs [1]. The most interesting example is the Microsoft Surface system, which is a table with build-in screen as a table top. The screen can recognize touch of any object, with an unlimited number of simultaneous contacts. However, although this table allows for multi-*touch*, it is not obvious to assume that it also facilitates multi-*user* interaction [2].

3.3 Shortcomings

The main key for success in the use of CSCW tools is increasing the users' willingness to using the tool. The tool must offer a solution for a recognizable problem. Current available CSCW tools lack the possibility to work simultaneously with multiple users at the same time at the same (or similar) task [3]. This should be extended with the possibility for conjoint use at multiple locations.

In looking at the currently used tools for collaborative work within product development teams, multiple aspects can be distinguished that hamper the quality and speed of the process. By dividing parts of the project among the team members, an environment is created in which every team member executes his part of the project on an individually most preferable method. The advantage is that during the individual work the chance of translation error or noise is minimal, because the user chooses the best suitable method for his part of the research. Obviously, this method will often align with the skills and experience of the user.

This immediately addresses the main problem in collaborative work: making all the research available and understandable for other team members requires an additional translation step. This translation step is often done during meetings where all the team members discuss the progress of the project. The translation is based on a summary of the work done and is guided by a direction for future research. Therefore, only the discussion is collaborative, the research itself remains individual. If a phase is completed by a team member, the complete package is handed over to the next department who continues to work on the information. There are often no iteration steps during the research, because that requires too much time and too often a translation of information to colleagues. Communication with colleagues is mainly done using computer software. Only during the meetings, face-to-face communication is possible; currently used software tools require computer based communication. Therefore, the communication is more often face-to-computer and vice-versa than real interaction and discussion on a face-to-face basis [4].

4 Envisaged Situation

Referring back to why collaboration is desirable within a project team, an envisaged situation which stimulates and facilitates collaboration is composed. In the new setting a fluctuating number of users are able to simultaneously interact with one system, independent of their physical location. The interaction possibilities are based on touch input using the body of the user (hands and fingers), but also offers the opportunity to use physical objects as input device. The wide variety of interaction possibilities, without predefined physical objects such as a mouse, creates an open setting, where users from different fields of expertise can generate and use their most preferable input method. Visualizing and communicating information among team members is done on a large scale setting using interactive projection walls, and on a smaller scale using tables with build-in projection screens. These screens are capable of detecting any kind of object and motion on the screen surface. The input generated by the users can be directly used in all kinds of multi-user software, varying from documenting till engineering applications. The combination of interactive tables and walls creates an environment in which the users are provoked to use the systems, mainly because the interface is not based on predefined hierarchies or interaction methods, the CSCW tool will have a low threshold.

To achieve this envisaged situation, new multi-user techniques need to be implemented in a collaborative work setting. It is important to realize that multi-touch is definitely not the same as multi-user. Multi-touch is a technology that can be the basis for multi-user, but requires dedicated software applications to support it. Furthermore, the recognition of touch must not be limited to single points, but also shape and contrast of touch objects must be recognized. The interaction with the virtual world can be further extended by combining haptic devices for smoothing the transition between the real and virtual world. In line with that, the combination of 2D and 3D is also a key element that should be integrated in the envisaged situation. The tools must be experienced as a useful, not obligatory or restraining, tool to improve collaboration and discussion. The tools should not obstruct the normal face-to-face communication between people; therefore, for the average user the use of body-mounted hardware should be avoided.

At this moment there is no specialized software available that supports all the demands and needs to facilitate and stimulate collaborative work as described in the envisaged situation [5].

5 Multi-User Collaborative Tools

Working collaboratively on one computer system without being forced to have a clear, prevalent and predefined hierarchy is certainly uncommon nowadays. There is always one person responsible for controlling a system by means of for example a keyboard and mouse. The controls can be handed over to other people during the session, but the result is that multiple inputs from different persons cannot be processed at the same time. In other words, it is a change of hierarchy, instead of an outcome of collaboration.

This section explains technologies that can be used in CSCW tools to stimulate the collaboration of the team members. The envisaged tool offers simultaneously multiple user inputs on a screen with a low threshold for using it.

5.1 Multi-Touch Recognition

To make a projection screen touch sensitive, a motion detecting feature is added. This technique is capable of continuously detecting an unlimited number of multiple touch objects. Contrary to the limitation of normal touch screens, the multi-touch tables are capable of detecting all objects placed on the screen. These recognised objects are not limited to the mere coordinate of a fingers or special pointer; the shape of the object itself is outlined. The recognition is done using multiple cameras placed behind the screen at different angles. These cameras track the movement of objects placed on the screen by identifying change in contrast. The cameras are equipped with an infrared filter that filters out all the light except for the range of infrared light around 850 nm. Behind the screen are a number of 850 nm infrared LED arrays to spread an even infrared beam to the surface of the table (Fig. 1). If any object touches the table, the object will reflect the infrared light and the cameras will pick that up as a highlighted object (Fig. 2). The whole technique is dependent on invisible infrared light, and is therefore not influencing the people operating the table, nor is it influenced by any visible light.

Because the shape of objects can be outlined and recognised by the computer, the system can recognize changes in the shape of touch objects. Another interaction possibility is to detect special identity markers placed on the bottom of

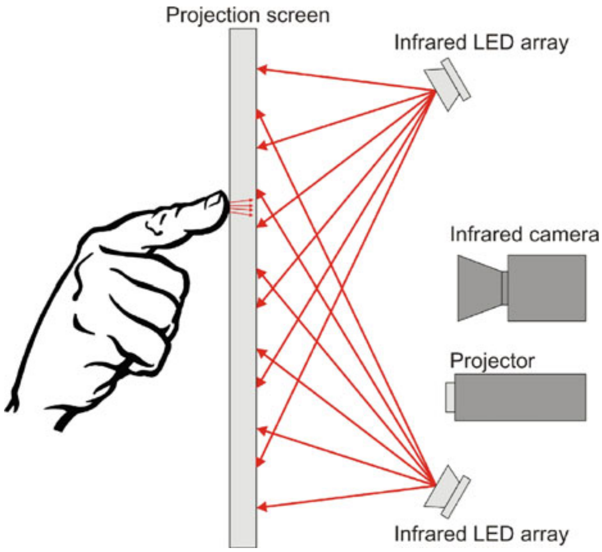

Fig. 1 Object detection principle

Fig. 2 View from camera

objects. These tags contain a unique code that can be used in the software to recognize and interact with the real object. Because cameras are used for tracking, objects floating up to 2 cm above the screen can be tracked. This technique can also be used to detect the (change of) angle and rotation of fingers and objects using shadows.

5.2 Multi-Touch Table

Computer screens often distract the user from face-to-face communication. A screen cannot be placed in the middle of the group of people due to the size and viewing angle limitations, and is therefore often placed on one side of the team with the consequences that the attention of the people

Fig. 3 Microsoft surface PC

is on the screen (or on the presenter), not on the other team members.

To combine the advantages of a virtual environment and face to face communication the use of multi-touch tables is stimulated. These tables have a build in computer screen that functions as both a real and virtual desktop (Fig. 3).

The screen is projected on the semi-transparent table top, and is therefore always present, but has no obligation for use as people will not notice it when switched off. The screen can thereby function as an information source, without disturbing the face-to-face communication possibilities. People can sit around the table and, without the need to look sideways or away from the discussion, information can be gathered. The screen also functions as an interaction system, where multiple users can simultaneously give input to the computer.

These multi-touch tables give new challenges for interaction possibilities and specialized software. Current software is based on use with vertical screens, which always have the same orientation on how the user sees the screen (bottom, top, left and right). This orientation is unknown in case of a multi-touch table. There are multiple users who see the screen from different angles and from different viewports at the same time, which means that the software cannot count on a fixed first approach on how someone will enter the software. The interface of those software applications can therefore not be compared to the currently available software used in CSCW. The challenge is to find new guidelines and interaction rules for future multi-touch and multi-user software [6]. As mentioned before, the users will initially not have any input tools (like keyboards and mice) available, but must be able to interact with the systems using their own fingers; in some cases also real objects can interact with the system using their shape (Fig. 4) or special identification tags (Fig. 5).

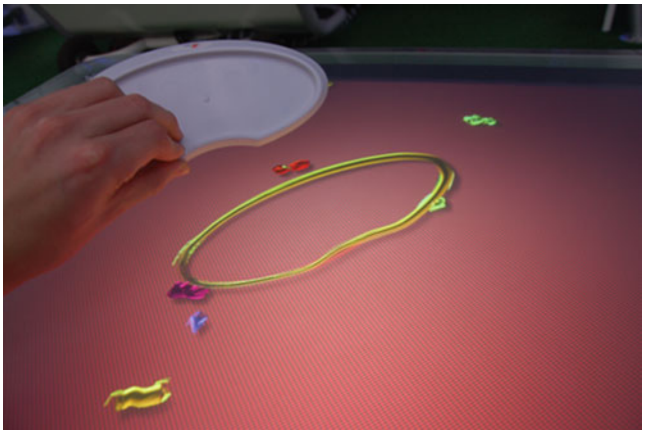

Fig. 4 Detection of shape and outline

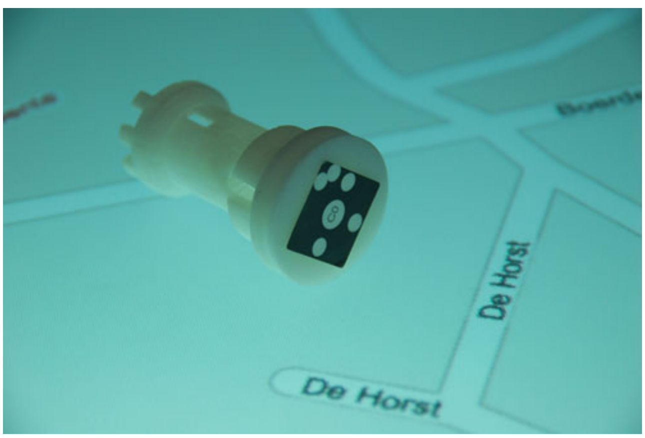

Fig. 5 Example of identification tag

5.3 Multi-Touch Wall

To test the ideas mentioned in Sect. 4, a full-scale multi-user multi-touch wall has been developed (Fig. 6). As mentioned, during the execution of product development projects a large amount of data is generated by each team member. Meetings and discussions are held to publish and present information to each other, but often also have the goal to arrange and link information to other parts of the project. Arranging and presenting a large amount of data requires enough space to visualize the information. This results in a large projection area, but the amount of information it can contain is very limited due to the distance. Moreover, this configuration again stresses the hierarchical relation between the presenter and the audience.

However, for arranging large amounts of data a large high resolution screen, with the possibility to stand in front of the screen with multiple people is practicable. This encourages the collaboration and communication between the people

Fig. 6 Multi-user multi-touch wall

since they all look at the same screen and all receive the same information.

Because the screen is close to the user, people can point at it and discuss it with others, without requiring any prior hierarchy. To enhance the collaboration and discussion further the users are be able to interact with the screen using multi-touch technology. This interaction makes it possible to adjust the information on the screen directly by multiple people during the discussion. There are no additional tools needed for the user to interact with the system, the screen is capable of detecting touch by fingers or hands. The multi-touch wall increases the discussion during the meetings and makes it possible to arrange information collaboratively with other people without having to wait for each other or being dependent on the input of other people.

6 Implementation

Multi user multi touch interfaces can be seen as a “natural user interface” (NUI); this successor to the currently used “graphic user interface” (GUI) offers a new approach to how software should be made. It forces us to think again about how to use computers, just as the transition from “command line interfaces” (CLI) to the current GUI made new input methods possible. It also brings new guidelines about how people should use a computer and what kinds of interaction are commonly used within most software. These guidelines are based on the limitation of the current systems, including the possible interaction methods.

Current software is not based on multiple inputs from one user, let alone multiple inputs from multiple users. The software often depends on input steps with fixed sequences, causing the software to perform a set action. Because all input steps are made by one user it is easy to track those steps, but it is impossible if multiple people simultaneously create multiple inputs on the same computer.

The implementation of multi-user and multi-touch products requires a different approach to computer use and of course adjusted guidelines for designing and writing software. The main goal of the software is to minimize the problems of translating the thoughts of the user to an understandable input for the computer system [7]. The new input methods minimize the translation noise we now often encounter when using current input devices. The software should also encourage the interaction with multiple users simultaneously, without having the hierarchy we see nowadays where one person is in charge and others give instructions. This multi-user approach makes it easier to use the software on different location at the same time, enabling interaction with the system on different places in the world simultaneously.

This creates new opportunities to work in one virtual environment with team members across the world. The same virtual world can then be shown as a copy on all the screens and the multi-user input possibilities from the software enable interaction to take place on all the screens. People can participate in the same virtual environment independent of their physical location.

Because large wall projections or large table screens can provide the users with a large amount of data, the risk of overwhelming the user with information is severe. The new software will therefore only offer the users the information needed on that moment, not more. By using filters and by identifying the task of the current users, the software presents only the (at that time) necessary information. This approach enables the users to work with large amounts of data without having to filter the information themselves; all information is constantly present in the software, but not always visible to the user.

Fig. 7 Integration of real objects in a virtual world

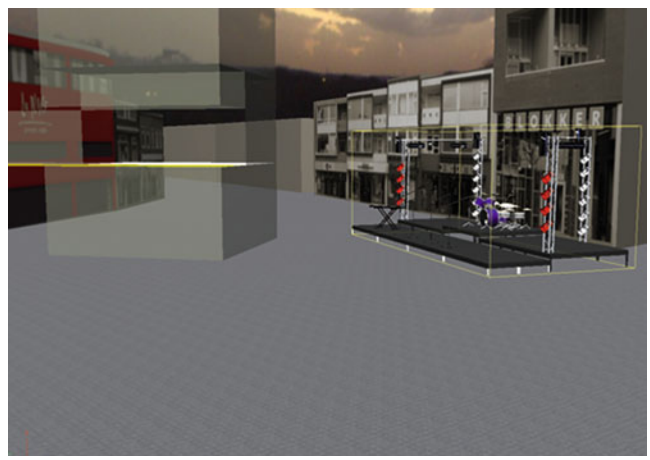

Fig. 8 3D rendition of 2D input

6.1 Combination of Techniques: Case Study

A very interesting application currently under development combines nearly all of the possibilities of the multi-touch and multi-user tables and walls. This program enables users to arrange physical scale models on a table (Fig. 7) and simultaneously generate a real-time 3D environment on a large projection wall (Fig. 8). These physical scale models can be used to arrange the setting of objects on all kinds of locations, for example inside buildings, like supermarket interior, but can also be used for arranging buildings or objects in a city. With this application the multi-touch table is used as a top view map of the area where the objects in real life will be placed, the physical scale models can be placed and arranged on the surface of the table. Arranging and generating an environment using real models stimulates the multi-user collaborative work. Multiple people can arrange the models by simply picking them up and placing them on a new location; the computer detects the location and orientation of the objects. The software gives feedback to the users on the consequences of placing objects in that specific order. It can for instance provide the users with information if an object needs a clear space around it, based on the properties of the real model (like radiation, ventilation, walking space, etc.). If specific objects are placed too close to each other the software can urge the user to rearrange the items using visual feedback. The software is also capable of providing the user with evaluation information about the current setup. This can for example include information like the amount of wires needed, the underground infrastructure, the predicted costs for installation and maintenance, the expected problem areas and whether or not the setup fulfils are the legal demands (all of course dependent on the type of environment created).

The location information of the physical objects, detected by the multi touch table, is used as input for the 3D environment. This 3D environment generates a real time virtual instantiation of the setup made on the table. This enables the users to review the setting in an interactive virtual world presented on a large multi-touch wall. A large multi-touch wall makes it possible to review the setting with multiple persons, and include details and objects on any desired scale. It is possible to walk around in the virtual environment to get an impression of what it will look like in reality. Walking around can be done using the multi-touch possibilities of the screen, where the users can indicate the direction in which they want to look and/or move. Changing the camera position can also be done using a scale model of a character which is placed on the multi-touch table, in which the viewport of the virtual camera is the viewport of the physical scale model of the character. These 3D environments provide information on how the line of sight will be in the real world, enabling the users to see if objects block the line of sight, and how the view will be from existing locations (for example the future view from current windows in a city). It also enables the users to review the visibility and proportion of the objects, and allows interaction with the new products in the virtual setting. The interaction possibilities and feedback of the objects are show in the 3D environment, so that the interactions can be performed (for example pushing and pulling objects) and evaluated before building the objects in real.

This combination of new interaction methods and products, in combination with software made especially for multi-user and multi-touch use will stimulate the collaborative work during projects. The software increases the quality of communication and prevents the occurrence of a fixed hierarchy in users and in use.

7 Future Development

Multi-touch interfaces are a great new way of human-computer interaction, which offer a new approach for developing design tools to support and stimulate collaborative work. Multi-touch interfaces can be seen as the first step of natural user interfaces, although some options are still not possible with these new interaction techniques. Especially the feedback to the user does not make optimal use of all the human senses.

One of the focal points of future development will be providing better visual feedback to the user in the form of a 3D image. Current 3D visualization tools do not stimulate the multi-user collaborative work. Most techniques force the user to wear head mounted devices to visualize a 3D image. But additional hardware on the (head of the) user obstructs the face-to-face communication with other people. The virtual world generated by those techniques is based on a single user experience, and therefore hard to use in a team setting. Another method for showing 3D images is by using 3D monitors which show 3D objects without the need to wear glasses. These monitors can be easily integrated in a team setting, although the monitor has the same drawback as current projection screens: it is placed on one side of the room, and therefore will not stimulate the communication between people.

The most interesting future option for showing a 3D image is by using holographic tables. Above these tables holographic 3D products float in the air, and can be viewed from every angle. Multiple people can look at these objects and discuss it with others around the table. Because the object is projected above the table, between the people, it is in the centre of the meeting and will stimulate the discussion. Consequently, it will not block the face-to-face communication, nor is there a need for additional hardware mounted on the viewers of the hologram.

Holographic displays currently have one major drawback compared to multi-touch interfaces, being the lack of interaction possibilities. Interaction with the holographic display is also a new way of interacting with computers. Instead of working in a 2D environment, interaction occurs in full 3D environments. The goal is to combine the touch interaction of the multi-touch systems, with the visual feedback of holographic displays. The interaction with those holograms should be done by using the hands and fingers of the user; this gives the lowest threshold for using the system, and does not require specific expertise of the user. It makes it also possible to interact simultaneously with multiple people on one model.

A second focal point for future development is the tactile feedback to the user. In the current multi-touch environments, every touch feedback to the user feels the same. There is no difference in feedback possible because the user touches the static material of the projection screen. This is even a bigger issue with holographic displays because they contain no fixed material, and therefore are difficult to touch. A combination of new techniques is required to make it possible to feel virtual objects in the air. The developments in this area can be split up into techniques that provide feedback by adding hardware to the body of the user, and by techniques that are independent of additional hardware on the body of the user. By adding, for example, a glove or muscle stimulators to the body of the user it is possible to give the user the feeling of feedback. The glove can block the movement possibilities of the hand, resembling the feel of touching objects. The same can be achieved by influencing the muscle tension by using muscle stimulators; they can also block the finger movement. Both techniques require additional hardware on the user, which is not preferable in a collaborative work session. Therefore, techniques that are independent of additional hardware on the user are most interesting for use with holographic displays. These techniques give the user feedback by sending focussed ultrasonic waves to the touch areas of the user. Depending on the accuracy and resolution of the ultrasonic waves even a texture and relief can be experienced. The combination of this tactile feedback technique and holographic displays for visual feedback is one of the best examples of natural user interfaces.

8 Conclusion

The successor of the current graphic user interface (GUI) is called natural user interface (NUI). The most important aspect of a NUI is to decrease the translation noise that occurs by translating thoughts into understandable computer language using keyboard and mouse. Multi-touch products offer the opportunity to interact with computer systems with a variety of body movements, thus lowering the threshold of using a computer system because there is no need to learn how a computer input tool works. The use of multi touch systems is already visible in an increasing number of products. Current software tools are adjusted to work with one-user multi-touch. The biggest opportunity of multi-touch products, however, is the possibility to use it with multiple people simultaneously. The main bottleneck is the availability of multi-user software; the technique as such is implementable as shown in the multi-user multi-touch wall.

During projects people work often in team settings; the synergy within the team is the key factor to success. Every team member must be able to present, communicate and discuss his research findings. Collaboration between different people often results in communication to each other using the displays instead of face-to-face communication.

With the use of multi-touch techniques new design tools are generated for use in multi-disciplinary product development teams. The technique offers the opportunity to work together simultaneously on the same (or similar) topics by different persons. Multi-touch techniques do not require any new specialized input tools; therefore there is a low threshold for using it. Besides that, it will not obstruct the direct face-to-face communication between people, and is not dependent on a fixed hierarchy amongst the users.

The biggest challenge now is developing the adequate software that enables multiple users to work together on one computer system, independent of the user's background or field of expertise, but also independent of the physical location of the user in relation to the screen. Therefore, the aim is to develop new guidelines for software developers and software users that indicate how interaction with multi-touch multi-user systems can be employed.

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The Collaborative Product Design and Help to Decision Making: Interactive Mind-Mapping

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Abstract This chapter presents a state-of-the-art of design from the main definition to the more specific aspects of product design. We focus on communication problems and social aspects of the design process in a collaborative context. Afterward, we concentrate on the decision making problem in order to determine a work hypothesis in the mind-mapping area. In this chapter, we report the development of our idea which results in the conception of an interactive mind-mapping technique on a multi-touch table, called mindflow.

Keywords Mass customization · Knowledge management · Product design

1 Introduction

In this chapter, we propose a state-of-the-art about collaborative product design. In our approach, we consider the product as a physical and tangible artefact. The first part aims at summarizing what characterizes the collaborative design and at highlighting the difficulties encountered by design groups. The second part tries to propose a solution to solve these problems and especially to facilitate decision making: the interactive mind-mapping with a multi-touch screen.

2 Design as a Problem-Solving Process

2.1 Definitions

We can define design in two different ways: first, as an action to create and elaborate something, from an idea. This first definition is commonly accepted by the community but can be completed by this second meaning, like a specific way to imagine or to envisage something. These definitions express that design is a mind process before being a physic process of construction. Even if only 5–15% of the time is dedicated to the "mental design" [1], this first step of abstraction is of primordial importance: it instigates the entire project in a specific direction.

2.2 Problem-Solving and Problem Setting Approaches

Design is seen as a "problem-solving approach": the starting point is a problem and the goal is to find a solution to this problem. If the problem is clearly defined, it will involve a resolution process; from this solution perhaps some new problems will appear and will involve a new problem-solving process. Design is seen as a Problem-Setting approach to: in the beginning, the problem is not fully given and part of the design process is to modelize it [2]. In brief, it is a cyclic and iterative process based on the couple problem/solution. The solution and the problem are closely linked since designers could establish a connection between a new problem and former problems previously solved and apply the same solving approach [3].

2.3 Multiple Solutions

The design approach can lead to many different solutions, and many different ways to solve a problem. Even if the approach is based on a unique proposition, there are multiple solutions. The number of internal and external factors into play is too important for different designers to imagine exactly the same solution. Only one parameter, even on the everyday life of the designer, can modify his point of view and his approach to solve the current problem. It is impossible to meet all theoretical expectations expressed at the beginning of design project; the point of view of the

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designers, or of the people involved in the project, can have a strong influence on the nature of the compromise and wherefore on the design process.

2.4 The Dependence of the Viewpoint on the Solutions

The concept of "viewpoint" is essential to understand the problem-solving process. However this notion is rarely described and explained in the literature dealing with individual conception: it is an emerging concept, like intermediate representations [4] and appears when research focuses on collaborative work [5]. The "viewpoint" corresponds to the way of thinking of the designer, that is the difference of concept's abstraction regarding to the problem solving, compared with another designer [6]. The choices previously made during the process, the choices of work methodology, the targeted users, and all the variables and choices made during the design process stem from the designer's point of view. It is the reason why different points of views imply multiple solutions and possibilities. This concept of "viewpoint" is of paramount importance on individual design, even if it is somehow implicit and not fully visible, and becomes essential in collaborative design [7]. During the collective design process, variation in viewpoints will lead the project to different ways, and the combination and fusion of the different points of view are essential to enhance the creativity of the solutions. The product design is fully dependant of this concept.

3 Production Design: A Collaborative Activity

3.1 Evolution of Product Design

In this chapter, by products, we make reference to an "object", a "tangible artefact". Jacques Monod defines it as "a Product of the Art and the Industry" [8], it is an artificial object which is opposed to real ones. The design process activity is both really specific and wide, which had knew a lot of changes on different aspects since many years. These activities' transformations are noticeable from a technical point of view but also from a social's one inside the design process.

With the increasing complexity of the products, design teams involved in the life cycle of the product become bigger and multidisciplinary [7]. The management of the complexity of the design process is a major problem of the concurrent engineering. The activity could be seen as a group of designers, with expertise in various fields, seeking to collaborate in order to create the final product that is an artifact, resulting of multiple viewpoints crossed [9]. The product design's history starts with the "additive cooperation" which combines the skills and the efforts of a group in order to accomplish a task which is impossible for a single person. Nowadays, the technology's advance allows reaching a new step: we can talk about "integrating cooperation". As a consequence of actors' specialization, based on very precise working skills, projects are made up of the sequence of all of these constitutive parts [10]. Moreover, several activities' factors are involved in the collaborative design process, which opens as much new avenues of research: collective decision making, problem solving through cognitive process, knowledge and skill management, organization constraints, social links [11]. The aim of this part is to understand the process of the collaborative design, always linked to the product design, and to extract some key features as guidelines of this project.

3.2 Organization of the Collaborative Work

3.2.1 The Couple Space/Time

The Computer Supported Co-operative Work (CSCW) introduces the fundamentals of the commons-based peer production, based on two main concepts which are "the time and the space". Johansen (1988) proposes a matrix where these concepts are crossed to create four different work's structures [12]:

- The temporal approach of the communication, which can take two values: "synchronous", at the same time, without time-lag and "asynchronous", with time-lag.
- The spatial approach of the actors, on two aspects: "co-located", on a same space and "remote", in different spaces, with a distance between them.

The spatio-temporal parameters are crossed [13] in order to create four different situations (see Table 1).

Despite the fact there are four distinct work methodologies, problematics of use are close. It is the reason why a system thought for an "asynchronous & colocated" work can create close interactions with a system based on a "asynchronous & remote" context.

Table 1 Communication depending on space and time

	Co-located	Remote
Synchronous	Face to face conversation	Telephonic conversation
Asynchronous	Post-it	Letter

3.2.2 The Collective Design Typology

Design, and especially industrial product design, can be separated in two main collective design concepts: "codesign" and "distributed design".

In distributed design, also called "exclusive collaboration" [14], actors work on the different parts of a same project by regularly exchanging their point of view and by consulting each others. Everyone is an expert in his area and can modify his methodology and his comportment regarding to the evolution of the project: in this situation each actor is neither necessarily aware of the others nor their activities; they are cooperating only through their workspace [10]. This approach is based on the task parallelization of each worker, each of them has is role in the project, so the organization is the first factor of success. It is a well tried method after all from the productivity viewpoint but it requires a high collaboration sense, as everyone has to feel himself implicated in his area and try to reach both personal and collective goals [15]. This method also needs a strong structure, and requires some concessions from each actor. Furthermore, the collaboration does not reconsider the decisions made by each actor independently. However the solutions can be original and creative.

This methodology is often opposed to the "dictatorial collaboration" where the actors chose a leader who will head the process. This kind of collaboration implies that the leader has a role of interface between the actors of the project: he has to translate, understand, transcribe again, in order to create group cohesion. This leader is the person who makes the decision. Finally the fact that one person is an intermediate between all the members risks to weaken the group emulation [16].

Co-design [3], also called shared cooperation or direct collaboration, is the strongest collaborative methodology where every actors work together, in a same global space. This process is synchronous and each actor perceives the work of the others and can react in real time. The designers share a common goal, where everyone can express his viewpoint on every part of the project, regarding to his capacities and his knowledge. If the process is not correctly structured, this method does not give efficient results [14], because each actor wants to impose his idea and stands one's ground. This global observation is less visible when the group is composed with people with an expertise in the same field, because the communication is easier. Without a doubt, the communication is an important point for a multidisciplinary collective work.

In this co-design category we can distinguish two subcategories [17]: pure co-design and supervised codesign.

In pure co-design, the evaluation and the decision making are based on a common agreement between the co-workers. Conversely, in supervised co-design, the final choices are made by one person, a supervisor. The designers are constrained in their choices. Furthermore, this hierarchy involve some restriction in the propositions of each actor and, often, through a specific communication protocol.

These two prevailing methods lead to organizational, social and technical constraints. These two main points are, for our work, two totally different approaches and it is necessary to go further into details.

3.2.3 The Inter-Experts Communication

In collaborative design, the work is based on the various skills of the actors, which allow broaching a project with several points of view. The personal vision of a project and the unique viewpoint on the problem solving is expressed by each actor through communication tools and often during meetings. These phases are essential for the development of a product design process, and involve many processes and activities.

Interactions and relationship constraints, involved by the collaborative work, are guided by two complementary goals: the operating synchronization and the cognitive synchronization [6].

The operating synchronization allows to define the allocation of the tasks for each actor of the project and the temporal distribution of this actions. Each person involved in the project has a specific post and a role, and everyone must agree with the organization. It is a main point, especially in distributed design.

The cognitive synchronization is an important issue for the progress of a meeting, to make it efficient in terms of propositions, problem solving, decision making and evaluation by the group. The aim of this synchronization is to establish a context of mutual knowledge, and to build a common operative system of reference [18]. All the designers must have the same knowledge of the project, of the goal of the meeting and of the involved choices.

This synchronization is not necessarily perceptible, but is mandatory. Furthermore, if this synchronization is not mastered, a slowdown of the real activity of co-design could occur. Visser shows that the cognitive synchronization can use up to 41% of the meeting time [3]. Even if people seem to agree on the elements and on the prerequisites at the beginning of a meeting, this synchronization falls down progressively and reveals some divergences, followed by a complete review of the context and so on. . . This problem is partially due to the lack of comprehension between the experts and the lack of reference medium.

The operative language is created by the ultraspecialization of the actors. Each designer is attached to a specific profession and, consequently, attached to a specific lexical field. One word can be very precise and have a specific and unique meaning for one expert (who think he expressed clearly his idea) but will be totally confuse and imprecise for another designer working in another field. The worst of it is that this word has also two different meaning. This linguistic problem, highlighted by Ferdinand de Saussure, the signified is expressed by the signifier and the signifier is used to express the signified. A linguistic sign is composed of one signifier (acoustic image) and one signified (global image). In a specific context, a signifier is not related to the same signified, which designates the concept, that is the mental representation of something.

The various points of view with regard to the solution of a given problem, lead to exchanges and argumentation between the actors of the project. A kind of debate is launched in order to exchange some ideas in a phase called "cooperation of debate" by Beuscart. The aim of the meetings is to transmit, communicate, propose, criticize and share ideas in order to speed up the debate. This cooperation is used to select ideas between the ones proposed. But, like the cognitive synchronization, we have to highlight problems of communication and interpretation because of the different lexical field and work background. It is the reason why some decisions are badly transcribed, which causes mistakes in the design process. The bad definition of the problem, the lack of information and the language barrier are factors which accentuate the lack of structure of the solutions [6]. The validity and the veracity of a decision obtained by a process based on the knowledge are flimsy and questionable [10].

Implicitly, since the beginning of this research, our point of view was always focused on communication problems, i.e. exchanges between the different actors a project, with different skills and backgrounds. The organizational aspect was potentially an interesting research solution. But problems in operative language, cognitive synchronization, debate cooperation, etc... are the starting point of the research project presented in this chapter.

3.2.4 Intermediate Representation

The intermediate representations are in the continuation of the communication process, because an object has a life before being released physically on the market. An object begins with an idea, is transformed onto rough sketches, is improved with other ideas and creates new ideas. It takes his shape and his properties little by little; some ways are abandoned, others are selected or pushed aside. Day after day the product adopts different shapes, called intermediate representations: they are the traces of the evolution of the product and the basis of the work between people. They are the representation of every aspect of the product (technical, shape, etc...). The intermediate product is a help to the deductive reasoning and the formalization of a problem and the research of solutions. The intermediate product is the materialization, the memorization of the decision making process of a project [19]. Intermediate representations are essential for the development of a project in order to understand the different aspects of a product and to evaluate it [20]. The definition of Neelamkavil confirms this aspect, considering an intermediate representation as "a simplified representation of a system (or a process or a theory) intended to enhance our ability to understand, predict and possibly control the future behavior of the system". These representations are also excellent communication media in a multi-disciplinary design team, because they are independent from external elements.

The intermediate representations exist from the first sketches to the final prototype before the production which is very expensive for the company. But more and more companies use virtual representation of their products in order to limit the cost and to have the opportunity to easily modify an aspect of the product without having to remake a physical prototype. These representations are the keys of the collaborative design.

3.3 Collective Decision Making

During our research one key word was revealed: the decision making [21, 22]. The decision is defined as "the action to make a well-considered choice of a solution after a deliberation". The decision making is integrated on a process [23]: deliberation, decision, production. For an individual work, deliberation and decision are often implicit because they involve only one actor. But in a collaborative context, the information's sharing and the debate between actors before the decision making are essential to widen the possibilities and the number of choices. The collective decision making is a part of a group of potential choices elaborated in a cooperative way [24]. The decision corresponds to one instant in the process, a transition between two states.

4 Problematic and Hypothesis Emergence

4.1 Observations from the Literature

The different aspects of the collaborative design presented on the previous parts, raise some questions about the inter-experts communication around the decision, and especially about the methods to assist the decision making.

A first coarse-grained question can be: which feature does a system implement in order to make the decision making efficient in a multi-disciplinary team?

Regarding the decision making support, a system cannot take the work of an actor (i.e. by choosing a solution). The designer must master the decision, because of the infinite number of variables and subtleties that a system cannot handle. But working on the decision making is also considering two correlated aspects: how to make and prepare the decision? How to work after this decision?

We can reformulate our problematic as:

How to help the decision making around a product in a multi-disciplinary product's designer team?

Consequently we decided to work on a major issue and to focus on very specific contexts in order to extract some common problems. The aim is to suggest some new avenues of research.

4.2 Reconsidered Context

This main line is based on the decision making in a context of pure co-design. All the actors are present at the same time in the same space: each actor, with a specific background, is equal and has the opportunity to express himself on every topic, without separation between expertise and without decisional actor. All the points of view are mixed in order to propose new ideas, describe, criticize, justify, argument. The aim is to make the right decision for the team work. It is a phase of debate cooperation.

4.3 Highlighted Problems

In this context, because the actors express themselves most of the time by speaking, and because their different backgrounds, the problem of operative language is still remaining. It becomes hard to correctly argument his point of view because it is always (badly) interpreted, which does not allow to broaden the choices and to increase the ideas' potential. By the way, the decisions are potentially not the optimal ones.

The retranscription and the idea selection are often put down in writing. But each actor is not involved in this process, only one or two persons handle this part; this situation creates interpretation mistakes. The person who writes up is often outside of the debate because he is involved in the writing process, and he cannot follow every part of the communication process. Information and data will always be missing because one actor will not express himself strongly enough compared to the other, or because by an implicit selection of an idea by the writer. Furthermore the linear progression of the writing is in opposition with the debate which is always in evolution and jumps from one subject to another. Moreover some actors will use external media such as pictures and different intermediate representations in order to increase the power of their idea; these media cannot be transcribed on paper.

4.4 Clarified Work Goals

This main line has different aims. The first one is to put the artifact at the centre of the debate, in order to highlight its properties, to use it as a support for the argumentation. Furthermore the debate must be able to use large range of tools in order to increase to power of the ideas and make them clearly understandable by everyone in the meeting. It is really important that every actor masters his argumentations but can also react from another idea advanced by another actor. Moreover this debate history must be always visible and somehow tangible to use it during the meeting period has an aid, and to keep the focus on the problems. It is important to create an interface allowing pushing aside some ideas, developing new ones and coming back to previous ones without cognitive stress. And by the way extend the choices without any risk to lose a potential good idea. Moreover the actors must be able to break down ideas as it is possible with physical products to analyze each part independently. The second goal of the project is to emphasize the main point of the meeting in order to aid the decision making. The underlying question is: at the end of the meeting, do we need to keep everything? The selection of the ideas is sometime as much important as the development of the ideas. Organizing data into a hierarchy is very important and could aid actors to choose the main decisions in order to finish a step in the design process.

4.5 Interactive Mind-Mapping for Co-design: A New Concept

This idea to develop and to break down the different aspects of the product around a central point was the starting point to the use of the concept of Mind-Mapping. The mind-mapping is a specific diagram representation, using semantic connection between ideas and hierarchic links between concepts. This recent method was created by Tony Buzan in order to break the linear lecture system which is at the opposite of the brain functioning. This "central thought" could be considered as an associative process from a central point which is the main idea. It is supposed to be more natural for the brain, using multiconnections see Fig. 1 for an example of mind-map.

This method structures the action of taking notes differently for each person or each group. Actually the shape of the resulted mind-map is unique and could potentially reveal the way of working of the team. For the person who works

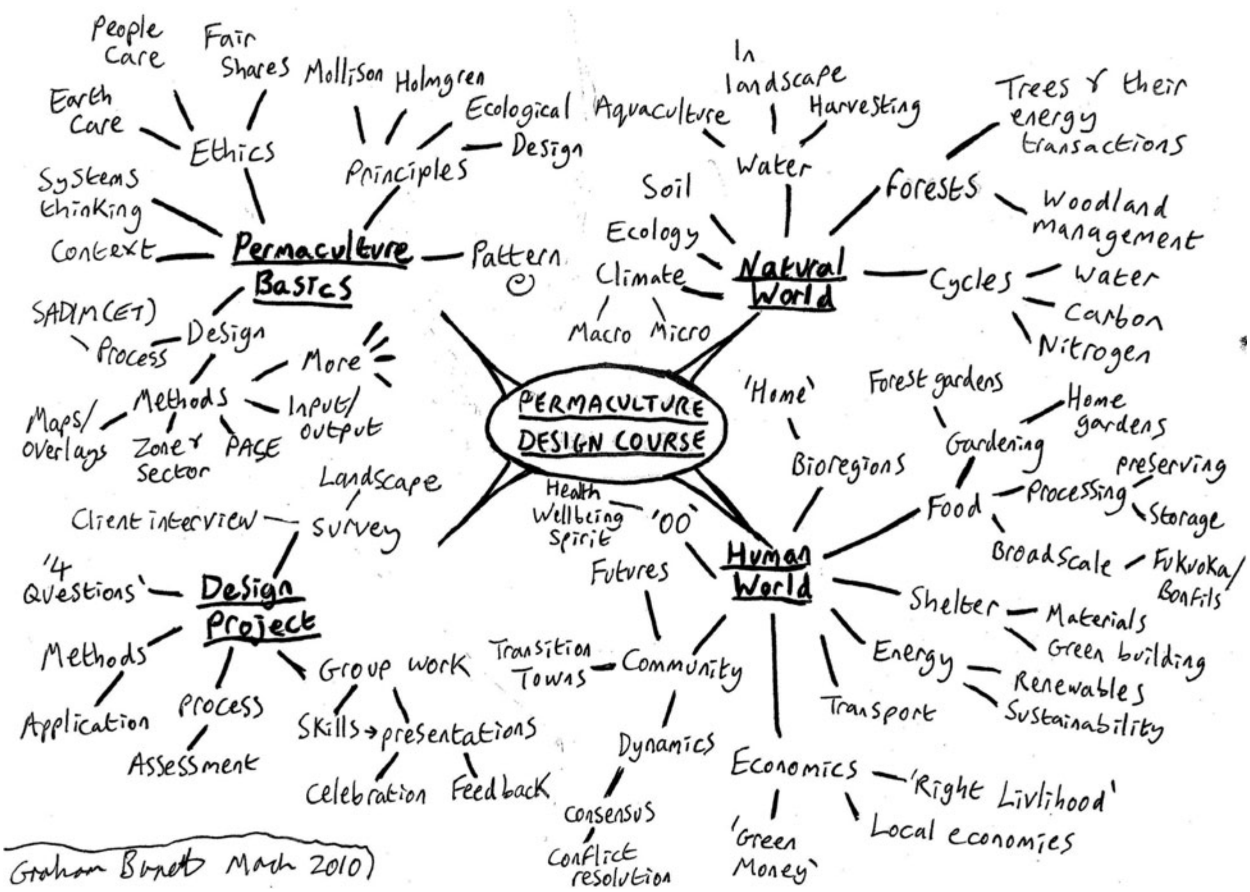

Fig. 1 Example of mind-map

on its construction it is very efficient because an overview of the map permits to mentally remember the dialogue and the argumentation, much more easily than with a linear notation. Because it corresponds to the way of thinking of the group, the associations of ideas are efficiently distributed over the map, and data could be easily evaluated.

Our problematic becomes: how the interactive mindmapping can help decision making in a co-design process?

5 Project Development

5.1 Experimentation: A Classic Mind-Mapping Session

5.1.1 Introduction

Before starting to develop concrete ideas of interface, we chose to create and analyze a classic small team's meeting around a paper in order to create a mindmapping with actual tools (paper and pen). The goal of this session was to identity advantages and drawbacks of a classic mind-mapping session in a collective context, from a concrete usage point of view but also from a communication and decision making point of view.

Mind-Mapping Session

Five people, with different backgrounds and different viewpoints, take part in the session. The goal was to debate and to confront and share their ideas. The topic of the session was not imposed to do not constraint the debate process: an open selection from all the members was made, in order to involve all of them in the process. The final topic was tangibilization of the numeric memory. To make to post-analyze of the sequence of events easier, each actor had a pen with a specific color, and the session was video recorded.

5.1.2 Results

Observations and analysis of the mind-mapping session and of the answers of a survey (after the session), give some interesting results, like future functions to implement and ergonomic details, but also on interactions between actors.

We present a list of user needs and expectations according to the present system:

- Move freely elements and structure of the mind-map.
- Provide a same overview of the map equal for each actor of the project. The main problem was the orientation of the text: some actors made some strange movements in order to write on the right direction, in order to allow opposite actor to read it.
- Highlight important elements during the session (sizes, colors . . .).
- Import external files (picture, 3D, sounds . . .): actors made references to pictures, videos, objects that they saw somewhere on internet or that they had on their computer, without the possibility to show them to team. Some actors used their telephone to show pictures. But these pictures are impossible to include on the map. So allowing external communication with PC, Telephone etc. . . is really important to have an efficient data flow.
- Distinguish each actors (by color or other visual clues) in order to facilitate the analysis of the map and evaluate the implication of each actor depending on the domain. At the beginning, this feature was developed only for the analysis, but the survey reveals a real interest for this method because it motivates actor.
- Keep the table configuration: being around a table is essential, as a classic meeting configuration is more efficient for the communication. The table is only a support, not a frontier between actors.

Far from the technical and purely ergonomic aspect, the mind-mapping seems to give a new interest to the debate. A real collective intelligence and a team unity are created. We observed the same behavior several times (especially at the beginning of the session): one actor, not totally self confident, hesitated to write down some of his ideas; another member took his color pen in order to write the idea and cheer him on to write himself his future idea. Everybody tried to participate. At the end, during the phase of selection, all the members felt involved in the process.

This experience of mind-mapping was particularly useful to confirm and refute some of our ideas and hypothesis. Furthermore it confirms that the interactive mind-mapping can be an interesting and pertinent solution during a codesign process, if we take into account needs and expectations of the users. It is necessary to adapt the basic mind-mapping in order to make it really usable in this specific context. We assume that a digital mindmapping could be more efficient than "paper-pen" one.

5.2 Concept Development

5.2.1 Technical Choice

We want to create an interface with the following features: intuitive, smooth, close to paper mind-mapping and appropriate to collaborative work. We choose to use a multi-touch table, because it seems to fall short of our requirements

5.2.2 Concept Design

The goal of our work is to create an efficient concept of interactive mind-mapping on a multi-touch table. In this particular project, body movements are essential, and it is particularly hard to explain all the ergonomic and interaction choices made for this interface. Selections and decisions were always made in a specific context of pure co-design, to keep the interface simple and efficient. The choices should have been really different if we had chosen to work on an individual mind-mapping interface (Fig. 2).

We could have explained features and details of the interface by writing them step by step on this chapter. After our argumentation in favor of the importance of the external media such as picture and video, think that the following videos are more efficient to explain the concept.

http://www.remanences.org/mindflow
(online: 25th April 2009)

Fig. 2 Presents the interface

6 Conclusion

The interface we propose, called Mindflow, allows to virtually break-down the artefact, to divide the product into categories and to analyze the different aspects composing the object, with a global point of view. It permits to extend the viewpoints on the project and develop new ideas. Furthermore the possibility to use a wide range of media allows each actor to communicate with his specificities and reduces the interpretation factor. The debate is facilitated. This interface becomes a visual composition of the communication process, helps the communication and provides a concrete trace of the collaborative work of the actors. It is potentially a tool to help decision making.

For the moment, it is hard to draw a real conclusion about this mind-mapping interface, moreover about the concrete decision making. The state-of-the-art permits to highlight some important points to develop a concrete concept by analogy. We think that the actual tool is not only potentially interesting for co-design, but also in other contexts than product design. Now our new tool has to be enhanced and tested in order to totally confirm our hypothesis.

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Integration Product-Process in Global Product Development

Integrated New Product Introduction Challenges in Aerospace Manufacturing Engineering

M. Maginness, E. Shehab, and C. Beadle

Abstract The key dynamic in supporting an efficient and effective new product introduction is the nature of the exchange of information between the functions of manufacturing engineering and design engineering. This chapter describes a study of this dynamic with particular regard to the role of manufacturing engineering in developing robust production process for the design intent. This study reports related work in this area and establishes the views of participants concerning product introduction process at a major aerospace manufacturer. It is found that integration between the manufacturing and design function driven by communication of qualitative data has brought benefit to the process in terms of quality cost and time. However, a stronger definition regarding the quality and usability of manufacturing process knowledge communicated to the design function is required for more effective and efficient new product introduction in the shortening timescales of the changing industrial environment.

Keywords New product introduction · Capability · Manufacturing engineering · Aerospace industry

1 Introduction

The development of highly complex products is traditionally achieved through the collaboration of multidisciplinary specialists throughout the product lifecycle. Understanding customer requirements and delivering product functionality that meets or exceeds them are achievements that bookend the programme of product development activities. Effective and efficient control of these activities provides a company operating in a highly competitive market with a profound advantage in delivering to customers a quality product in a shorter lead time.

New Product Introduction (NPI) is the business process that manages the delivery a cost effective product that meets customer requirements. It consists of the series of interacting decision making activities that bring a product concept to a state where a fully detailed design is defined and information is created that allows the product to be manufactured, assembled and tested [1]. Two key work owners are the Design Engineering and Manufacturing Engineering functions. Their efforts create mutually useful information regarding the product in development. Hence the transfer of information is an arbiter of effective processes in NPI. An integrated model of NPI supports the transfer of information to those activity owners that require it. The competition in the aerospace industry drives the need for New Product Introduction. Manufacturers of gas turbine engines are required to innovate new solutions to satisfy increasing demands from customers and regulators for ever more efficient engines that produce lower emissions, less noise and are sustainable commercial products. Adding to the challenge customer requirements give to product introduction are ever decreasing timescales for NPI activities.

Process efficiency is the capability demanded of NPI in the competitive environment. Efficiency improvements enable the programme of NPI tasks to be fully completed within a reduced timescale, while still satisfying customer requirements. This chapter seeks to determine the challenges these industry realities present to the work of Manufacturing Engineering and the role of integration in the NPI process of a leading aerospace manufacturer. The responsibilities of the manufacturing engineering and the span of product introduction activities within the complete lifecycle provide the scope for this research.

The remainder of this chapter is structured as follows: Sect. 2 describes the methodology undertaken in the research; Sect. 3 outlines the related work in this topic area; Sect. 4 describes the feedback on industrial practice from this research and Sect. 5 offers conclusions as to the challenges in

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new product introduction present in aerospace manufacturing and advocates future work.

2 Methodology

A series of interviews with key participants in the NPI process with the responsibilities of the manufacturing engineering function at the sponsoring company has been conducted. These interviews were approached in an open manner so as to capture knowledge of participants without presupposition as to the nature of the challenges experienced in the NPI process [2]. The opening question simply enquired as to the 'challenges' the interviewees could identify in the NPI work. By comparing feedback from interviews the gaps between aims of the process and reality and so the challenges in manufacturing engineering in fully achieving those aims would be shown. It was hoped that this manner of research could reveal new areas for more detailed future research.

Participating interviewees from the manufacturing engineering function included Product Introduction Team Leaders, Part Owners, a Manufacturing Technology Lead and a Process Excellence Manager. A Design Functional Coach from the design function was also interviewed to provide a balance of opinions. Interviewees where drawn from two supply chain unit production facilities. One performed precision casting and the other machining work. In this way a broad spectrum of opinion was hoped to be captured from these different processing specialisms with manufacturing.

3 Related Work

The work of product introduction in complex industrial settings is a widely investigated field. A review of literature in this area reveals a broad consensus that advocates a concurrent engineering approach enabled through the collaboration of specialist functions [3]. This paradigm is associated with an efficient and effective product introduction process that achieves the goals of high quality, cost effective products in a compressed lead time. The key enabling dynamic inherent in this paradigm is that of exchange of knowledge and information. The methods of enhancing this ability within complex product development processes remain the focus of much of the related literature.

Concurrent Engineering (CE) has been established over the last two decades as the dominant paradigm for achieving high quality new product introduction in a shorter lead time [4–6].This is the practice of simultaneously executing stages of product introduction traditionally described in a linear manner, typically as follows; product need identification, concept selection and detailed design followed by manufacturing system design, production, service and end of life retirement. The effects of early simultaneous manufacturing engineering activity alongside design, and the level of influence given to manufacturing over design are widely investigated phenomena [7–9]. Collins and Hull conclude that when designs are new, high levels of manufacturing influence at early product concept stages have the greatest positive impact on performance [10]. They identify that late influence from manufacturing in fact has a weak negative influence. Principal reasons put forward are more accurate decision making and reduced time to market. Better informed early stage design decision making, benefiting from collaborative involvement of downstream functions avoids the financial and time costs of late engineering changes to resolve problems. Commencing downstream tasks earlier also reduces time to market. The manufacturing function can begin the long lead time work of acquiring process capability and identifying material supply chains in advance of final product design definition releases, thereby enabling more immediate production ramp-up.

Cross-functional integration is the widely advocated strategy for supporting CE [11, 12]. It enables specialist functions to relate relevant information to one another in a timely and constructive manner to complete better quality solutions that meet requirements and are achievable within stable manufacturing capabilities. Integration embodies an approach to overcome the boundaries to communication that exist between specialist functions. Functional specialisation develops in response to the technical complexity of products. While functional specialisation provides the depth of knowledge necessary for robust product development, boundaries between functions identified in cultural, language and technological terms present a challenge to the flow of knowledge and information that is necessary for an effective process. Payne et al. and Bradfield and Gao emphasised that matrix management orientations are a commonly advocated organisational approach towards enabling collaborative integration within CE [13, 14]. It is an approach towards effective creation of cross functional teams that draw representatives from the specialist functions to collaboratively undertake a product introduction programme [13, 15, 16]. Teamwork is regarded as the means of ensuring full knowledge input from participants and that all requirements and constraints are agreed and understood by team members [17]. Beyond matrix management however, a growing body of literature identifies the role that the informal organisation plays [1, 18]. This is the network of relationships that grows organically in human organisations, crossing, and overcoming formal boundaries.

The principle of integration is the timely exchange of relevant information. It is identified that the products of product development are knowledge and information data [5]. Clark and Fujimoto propose five dimensions of integration that demonstrate the supportive role of integration on CE

[19]. They are; timing of upstream/downstream tasks, richness of information media, frequency of transmission, direction of communication, and timing of upstream/downstream data flows. Two refer to timing of tasks and information exchange (i.e. sequentially). The other dimensions describe the nature of information exchange within integration. Rich exchanges of information are optimal in face-to-face meetings. Immediate dialogue enables short iteration cycles as opposed to bureaucratic document based communication. Physical collocation of teams is widely recommended in this regard [9]. However an increasing amount of work acknowledges the problems collocation presents in organisations that have adopted a global approach to product development to leverage economic opportunities such as cheaper labour [13, 20]. High frequency transmission progressively provides other functions with partial information rather than awaiting singular batch shots at the conclusion of major work packages. In this way upstream and downstream functions are able to simultaneously progress their activities. Clark and Fujimoto's remaining dimension emphasises the importance of communicating in both upstream and downstream directions. The dimensions demonstrate that the nature of information exchange is just as important as the timing of the exchange.

The nature of how information is actually exchanged between functions is key to an efficient and effective concurrent and integrated product introduction process. Design for Manufacture (DfM) is a commonly used method for the formal communication of manufacturing process capability or requirements to the design engineers. A data driven nature of this communication to benefit the product introduction process is emphasised [21]. In this way the design intent derived from customer requirements can be assured through the alignment of production requirements with capability.

A broad consensus regarding the approaches to product introduction in complex industrial settings can be determined from a review of the relevant literature. Communicating knowledge and information between specialist functions is repeatedly cited as vital not only for enabling an efficient, and effective, concurrent process for the industry, but in achieving a cost effective product of high quality that satisfies customer requirements.

4 Industry Practice

In order to remain competitive in the aerospace industry it is incumbent upon the aerospace manufacturers to constantly seek opportunities for improving the design of their products to meet evolving industry and customer standards. The work of new product introduction is a vital process for achieving new components and complete product systems at the forefront of technical innovation whilst accomplishing stable and predictable manufacturing process capabilities. If components are intended for new products or are modifications to existing products they will be defined as 'new' and will hence such undergo the procedures of new product introduction. Concurrent and integrated work is the standard approach undertaken within the product introduction process. Integrated Project Teams (IPT) are formed in a cross functional manner to manage the development programme administered by a Product Introduction and Lifecycle Management model. At its top level the model describes the archetypal value adding development stages. At a decomposed level, it describes the relationship of respective function's individual (value adding) work packages to the high level project lifecycle and to other functional activities. Functional activity review meetings and formal product development stages scheduled throughout the process are occasions for specialist functions to meet together as IPTs and review product development progress against checklist criteria to ensure problems and risks in a programme are identified and measures put in place to address them.

The administration of Product Introduction joins a company wide drive toward ever more controlled, stable, efficient and capable business processes. Its role is to publicise information and 'how to' guides supporting these company goals mandating the work of product introduction to functions including manufacturing and design. Written quality standards embody guides for product introduction practice. Conformance to these standards demonstrates understanding and verification for all design and specification requirements. Manufacturing undertakes a 'right first time' policy. This describes the condition wherein a manufactured component conforms to quality and functional standards without need for time consuming additional iterations of rework. Components that fail in this regard have the potential to adversely affect the goals of the complete product lifecycle.

Manufacturing Engineering responsibilities involve achieving a stable and cost effective production process including defining the assembly scheme, tool design and quality assurance processes ahead of the production ramp-up. This short list belies the complex multitude of activities and interactions that these responsibilities entail. An understanding of these is critical for the successful completion of the responsibilities within the design window. The production of an aerospace component was used as a case study in this research. The component, when completed represents two major stages of production, investment casting and machining, before the processed part can be assembled in the complete product.

Defining each of these major processes for the components requires detailed work from manufacturing engineers to align the process with the goals of a controlled, stable, efficient and capable process. The two major stages of

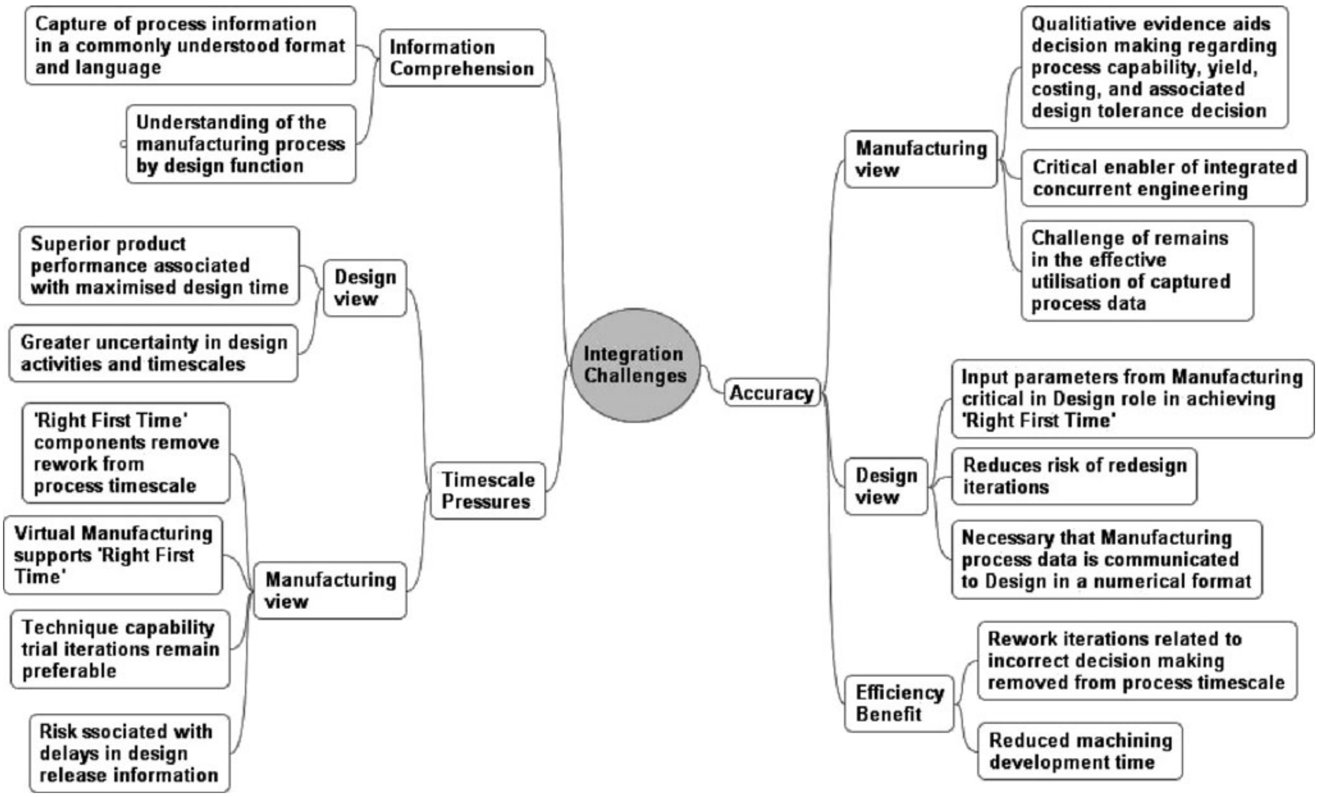

Fig. 1 Challenges in the integrated approach to product introduction

machining and casting respectively encompass a wide range of individual actions. The results of the interviews where summarised in through a mind mapping exercise (Fig.1). Here consistent terminology used in the interview responses was identified and grouped into themes. By this effort key topic areas relating to the challenges in the integrated approach to product introduction were synthesised from all the participants. The challenges identified are elaborated as follows:

4.1 The Challenge of Information Exchange

The common theme was information exchange between design and manufacturing, both in terms of quality, and understanding across functional boundaries. At the stage of the lifecycle where new products are beginning to be discussed at the level of component detail, manufacturing engineers can start the progressive work of defining manufacturing process capability for achieving final design intent. This can be commenced from a preliminary state. A capable process is one that delivers high levels of yield in production.

DfM is reported as a valuable dynamic here. DfM can be the forum from the earliest stages of component design for negotiating design parameters to enable a fully optimised product solution. Manufacturing can demonstrate a quantifiable capability can be achieved in a certain tolerance band and request design changes to tolerances to match, thereby reducing risk of low production yield downstream. Improving or acquiring process capability deemed vital to the design intent can also be identified and demonstrated early in the process through this exchange. Accurate, unambiguous data regarding process capability was repeatedly voiced as the vital element in this exchange. Historically danger lies in a manufacturing engineer basing decisions of whether a design feature could be manufactured on qualitative information. The design engineering view advanced in interviews is that accurate, data driven DfM exchanges enable equally accurate design decisions to be made, thereby limiting potential need for redesign iterations late in the process. DfM is the system where accurate exchange of process data is manifested to the benefit of the right first time policy.

For manufacturing the benefit lies in the ability to accurately predict production yields, and work this into cost models for the process. The data driven improvement in DfM is beginning to manifest itself in current projects that are approaching production ramp-up. A component currently in development achieved zero defects in a batch produced in an early proving run of a production process. Additionally machining development time on a current project was reported to have been halved from recent historic levels. The principle benefits of information exchange between design and manufacturing that is accurate and data driven are observable in both effectiveness, and efficiency. Better quality components result and wasteful iterations are removed from the process.

Here the key challenge on the part of manufacturing is the accurate capture of processing capability data. It was expressed that while the capture of data is well established in manufacturing, its translation into a useful format remained a challenge. A useful format was suggested as one that aligns with the management of information and data within the design function. Indeed it is suggested that the process of casting presents unique challenges in capturing its capability. Dynamics such as material properties of the cast material are more difficult to capture than machined dimensions. Further, a limited understanding of some of the activities of Manufacturing Engineering by Design Engineers is cited as a barrier to efficient interaction between the two.

4.2 The Challenge of Innovation

Advancing functional performance is vital for technological innovation that meets or exceeds customer requirements. Manufacturing capability must also advance to support it with a stable and controlled process. Design tolerances on components are reported to be increasingly sensitive with each innovation on efficiency and weight reduction. Competitors within the industry can be expected to be similarly driven to meet customer requirements. Tightening tolerances present a direct challenge to stable process capability and with that, manufacturing costs. The challenge of this work is added to by the compression of the time available in the project.

4.3 The Challenge of Timescale Compression

Ever decreasing time scales in which to complete the necessary product introduction work of manufacturing engineers is a major challenge driven by competitive factors in the aerospace industry. Key Manufacturing Engineering activities such as acquisition of physical process capability often have long and constraining lead times. Virtual techniques have been successfully developed to direct the definition of the manufacturing process to a more optimum level before any metal is cut on expensive tooling. For instance, in the casting process these techniques have been reported to have helped achieve production yields in new components at levels usually expected in mature production process. However limits to virtual manufacturing techniques are cautioned.

Not all physical aspects of the process can be predicted virtually. Hence it remains important to maintain physical trials and iterations of casting techniques to achieve a stable process. However an increasing pressure to immediate produce component parts for complete engine development limits this opportunity. As such the attainment of ‘right first time’ can be undermined and parts continue through the lifecycle at risk of future rework process iterations becoming necessary.

An attempt was made to identify whether the compression of timescales was equally distributed across the two functions of manufacturing and design. On one hand it was advised that the demands of individual projects and programmes are often too unique to provide such a generalisation. However, a common view expressed by manufacturing participants was that it was their work that often suffered due to late releases in design information. A design engineering view suggests that maximising the time available to design benefits a product that better matches customer requirements, which may add weight to the view that it is within manufacturing activities that timescale compressions may be felt most acutely.

5 Conclusions and Implications for Future Research

This chapter presents new product introduction challenges with particular focus on integration of the manufacturing function in the process. The research results support the view expressed in literature concerning the benefit integration of design and manufacturing functions has on the quality of the product being developed, and the effectiveness and efficiency of the product introduction process. The benefit derived from the recommended practices of rich and high quality exchanges of information are borne out in the aerospace company studied.

The responsibilities of the manufacturing engineering function can be seen to be supported by integration. Developing robust and stable production process, sustainable supply chains and accurate cost models benefits from the knowledge gained about the product in question from Design Engineers tasked to define it.

However, there is an indication that more needs to be done to clarify and define the extent of knowledge about manufacturing process that is necessary to improve design and the product introduction. It is identified that: (1) a definition of the manufacturing process knowledge required by the design function is necessary regarding the usability, clarity and quality of process data; (2) this definition must capture an understanding of the variety of processes used; (3) the definition must recognise the complexity of process specialisation within the manufacturing engineering function; and (4) innovative design requirements must be aligned with an evolving manufacturing process capability in this definition.

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A Multi-process Manufacturing Approach Based on STEP-NC Data Model

R. Laguionie, M. Rauch, and J.Y. Hascoet

Abstract Multi-process manufacturing calls for various competences and expertise. STEP-NC object-oriented approach proposes to unify several manufacturing processes in a common data model. Furthermore, CNC controllers are fully integrated into CAD/CAM/CNC numerical data chain. Thus, next generation of CNC machine tools promises to be more open, intelligent and interoperable. This chapter first proposes a simulation and optimization model for multi-process manufacturing environments by using STEP-NC. Then, a practical implementation of the developed concepts is carried out on the manufacturing equipments of the laboratory.

Keywords Multi-process manufacturing – STEP – STEP-NC – Process planning · Simulation – Extended CNC

1 Introduction

Over the past 50 years, significant advances in production technology, machines' capabilities, precision and speed have been lead by huge changes in the landscape of manufacturing competition and market evolutions. Companies that will early anticipate these fundamental changes by developing flexibility, transportability and interoperability for their production equipment will benefit from a large advantage to meet the customers' needs. In this context, intelligent systems, advanced control techniques as well as suited data exchange and programming standards will be required to support the increasing complexity of scenarios. Various manufacturing processes are developed to increase the productivity and the capabilities of manufacturing operations, each one involving specificities linked to the process itself. High Speed Machining (HSM) [1], Rapid Manufacturing (RM) [2], Electro-Discharge Machining (EDM) [3], Incremental Sheet Forming (ISF) [4] are examples of processes that can be used to manufacture a part. The choice of the most appropriate one is often linked with feasibility, quality, cost or production time [5]. Combining these processes can also be a well adapted solution, even for a single part. A lot of research works lead to push back the limits by developing new technologies, increasing computation and control capabilities and integrating the manufacturing processes into the numerical chain [6]. However, there is still a lack of interoperability in CAD/CAM/CNC numerical chains, which are using several processes and in the manufacturing process data management. This chapter introduces the interest of a common process data standard for supervision and simulation in multi-process manufacturing environments. After a brief state-of-the-art on multi-process integration in the current numerical chain, a new approach is proposed for simulation and optimization based on the STEP-NC object oriented programming standard.

2 Current Multi-Process Approaches

2.1 Current Programming of Multi-process Tasks

Any product development usually involves several manufacturing processes. Most of them are integrated in a conventional numerical chain, also called CAx manufacturing chain.

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The Computer Aided Design (CAD) system is used to create a digital model of the part. Then, manufacturing experts translate this global geometry into a group of machining features well adapted to a defined machining process, relying on their own experience. Even if a CAD file is only containing geometric data, the choice of a process to manufacture an area of the part leads to speak of manufacturing entity. A lot of factors can inflect the selection of the best manufacturing process: feasibility of the part, respect of the tolerances, availability of the process in the factory, knowledge of a qualified subcontractor, price, cost, manufacturing time, etc. but also some more subjective criteria linked to the experience of the experts, which are difficult to capture.

The model information is then exported to Computer Aided Manufacturing (CAM) software. The CAM software enables the user to add manufacturing data linked to the selected process. For HSM, data such as machine tool, cutting strategies, tools, workplan are used to generate the tool paths that apply to the features. These object oriented information is stored in a proprietary CAM format. Today there is no standard to exchange manufacturing data between the CAM software of different companies. The CAM software suites are often processing one single manufacturing process and the compatibility between several CAM software suites is hardly possible. A solution is to use a single vendor suite but it is usually not available for various processes (for example HSM, RM and EDM). Moreover there is still a problem if a subcontractor uses another CAM suite. Then the tool paths and manufacturing parameters are processed by a postprocessor selected for a unique machine tool. There are consequently as many postprocessors as existing CAM software/CNC/Machine tool configurations. The resulting low level information is translated by a postprocessor into NC code which is most of the time a G-code file based on ISO 6983 standard. For every process considered independently, there is a unidirectional information flow from CAD to CNC with no possibility to have an overview of the manufacturing data at the CNC level. In this context, there is a real need to dispose of a generic standard for manufacturing data exchange.

To make this numerical chain data flow efficient, multi directional data exchange is necessary. First, a feedback from CNC to CAD/CAM would allow a total integration of the process into the numerical chain. Then, a multidirectional data exchange between all the processes would lead to new possibilities for supervision and interoperability. A range of research works were carried out to design and implement intelligent CAD/CAM systems for CNC programming, especially for milling applications, but often restricted by the use of G-code machine tool programming [7]. However, few works have been done to create a link between the processes by using a unique numerical chain. There is no concrete solution in the current situation to support data exchange at the CAM/CNC level between processes that are culturally different and isolated inside their own numerical chain.

2.2 Multi-process Facilities

Combined turning/milling machine are increasingly used in the industry and provide large productivity gains and more flexibility. Combined machining programming also becomes more complex. CAM software suites integrate vendors' modules to improve the axis control involving complex algorithms for avoiding collisions. However, the numerical chain still sticks to basic unidirectional principles with no feedback of milling-turning interactions out of the vendor CAM software. To go further in the current "multi-process" approach, some machines tools are offering very different processes, as the "Desktop One" described in [8] which has milling, EDM and ECM (Electro Chemical Machining) functions. This kind of configuration is often limited to micro-machining applications. It demonstrates that combining these processes either on a single machine tool or into a unified numerical chain can be an efficient solution. Indeed, it takes advantage of their complementarities at larger frame, which is one purpose of this chapter. A multi-process environment means an environment where several processes can be used to machine a single part or an assembly, not necessarily by using combined machines tools.

2.3 Discussion

Multi-process manufacturing conveys an important stake for the future but it still relies on old and conventional ways of proceeding and thinking. The use of CAM proprietary standards, postprocessors and the structured low level information of G-code are today the main locks for a totally integrated manufacturing numerical chain. In this context, STEP-NC data model offers new possibilities within multi process manufacturing environments.

3 Multi-Process Manufacturing With STEP-NC

The STEP (STandard for Exchange of Product data model) ISO 10303 standard [9] has been developed to allow information exchange avoiding proprietary format. This standard is widely spread for data exchange in the case of 3D part model through the Application Protocols (AP) 203 and 214 and is available for data export on most of the CAD software suites. A new data standard, STEP-NC, is under development to integrate manufacturing information to the feature based CAD model built using the data structure of STEP AP224. STEP-NC refers to ISO 14649 Application Reference Model (ARM) [10] and ISO 10303-238 Application Interpreted Model (AIM) [11]. ISO 10303-238 is mapped from ISO 14649 ARM. ISO 14649 contains the process data structure. It describes workplans and workingsteps made of manufacturing operations, machining strategies, tools, machining parameters, etc. Object oriented STEP-NC programming offers new opportunities to support high level and standardized data from design to NC controller. It enables bidirectional data flow between CAD/CAM and CNC with no information loss at any stage of the numerical modelling. Several manufacturing processes are under implementation in STEP-NC data models and propose a multidirectional data flow to integrate the manufacturing numerical chain.

STEP-NC research has been conducted for several processes linked with researchers' main competence fields of manufacturing [12]. The first and most popular one is milling. Several international projects led to the first publications of ISO Standard 14649 Part 10 (general process data [13]) and 11 (process data for milling [14]) and completed with Part 111 (Tools for milling). These standards give the frame for STEP-NC milling. Turning applications are also included in the Application Reference Model of the STEP-NC standard. ISO 14649 Part 12 [15] gathers process data for turning and part 121 tools for turning operations. For hybrid turning/milling applications, Rosso et al. present in [16] the results of there study for the use of STEP-NC in manufacturing of asymmetric rotational component. Their conclusion is that the ISO 14649 Part 10 is capable of supporting the features required by these complex components and outlines a feasible solution to use the ISO 14649 data model for turn/mill machining. As STEP-NC ISO 14649 standardizes a data model for computerized numerical controllers, it is not restricted to milling and turning applications. ISO 14649 part 13 is under development for EDM data process [17] and research works are done in this field [18]. Some other works are done to build STEP-NC data process for Rapid Manufacturing [19]. By supporting all these different kind of process data, STEP-NC offers new possibilities to integrate, supervise, link and make interoperable all these processes in an integrated manufacturing numerical chain. Each process has its own specificities. The current G-code numerical chain results in insulating their implementation. Information available in G-code files cannot be exploited as it is too low level and only includes a small quantity of the data linked to the machining process. As STEP-NC supports a large field of object oriented data from CAD to CNC, it allows integrating multi-process relations with a common standard for several machining processes. Although STEP-NC standard proposes all the required characteristics to support a multi-process environment, very few research works were done concerning this approach. This chapter gives a proposal for the integration of intelligent multi-process supervision using STEP-NC numerical chain.

4 STEP-NC Multi-Process Programming

4.1 Intelligent Multi-process Systems

An intelligent multi-process system can be defined as a comprehensive system supervising autonomously several manufacturing processes with a minimum interaction with a human operator. STEP-NC standard provides a complete data structure that gives a support for information exchange of several numerically integrated processes. When the current numerical chain only relies on expert users' practices, STEP-NC offers new possibilities of integrating a comprehensive data support. It opens the way to a strong communication hub between experts by using a common well adapted language but also provides a data support for computational simulation and optimization of a multi-process workplan.

4.2 Multi-process STEP-NC Programs

STEP-NC file is an innovating support for manufacturing data and a large part of the work consists of building this optimized and well adapted file for intelligent manufacturing. The data structure of a STEP-NC file can be schematized by several overlapped parts of a puzzle describing a complete scenario (Fig. 1). To build the STEP-NC file, a hierarchical method is adopted. From the CAD model, the manufacturing features recognition is operated based on their compatibility with a chosen process. They are then sequenced to create the workplan, which consists in a list of workingsteps. A STEP-NC CAM software enables the user to select process data for every workingsteps. The STEP-NC file is then completed and can be sent to the NC controller. An interpreter in the CNC reads the object oriented data in the STEP-NC file and generates the tool paths which are well adapted to the production equipment. A machine functional model is available and can be included to the process simulation. The main principle is the same at the CNC level for each process required in workplan. Data feedback is available from CNC to CAM/CAD as any process data or geometry modification is directly reflected in the STEP-NC file, even at the shop floor level. Experience capitalization, in the STEP-NC file if needed or in a database, and can be exploited for building or optimizing STEP-NC file process data.

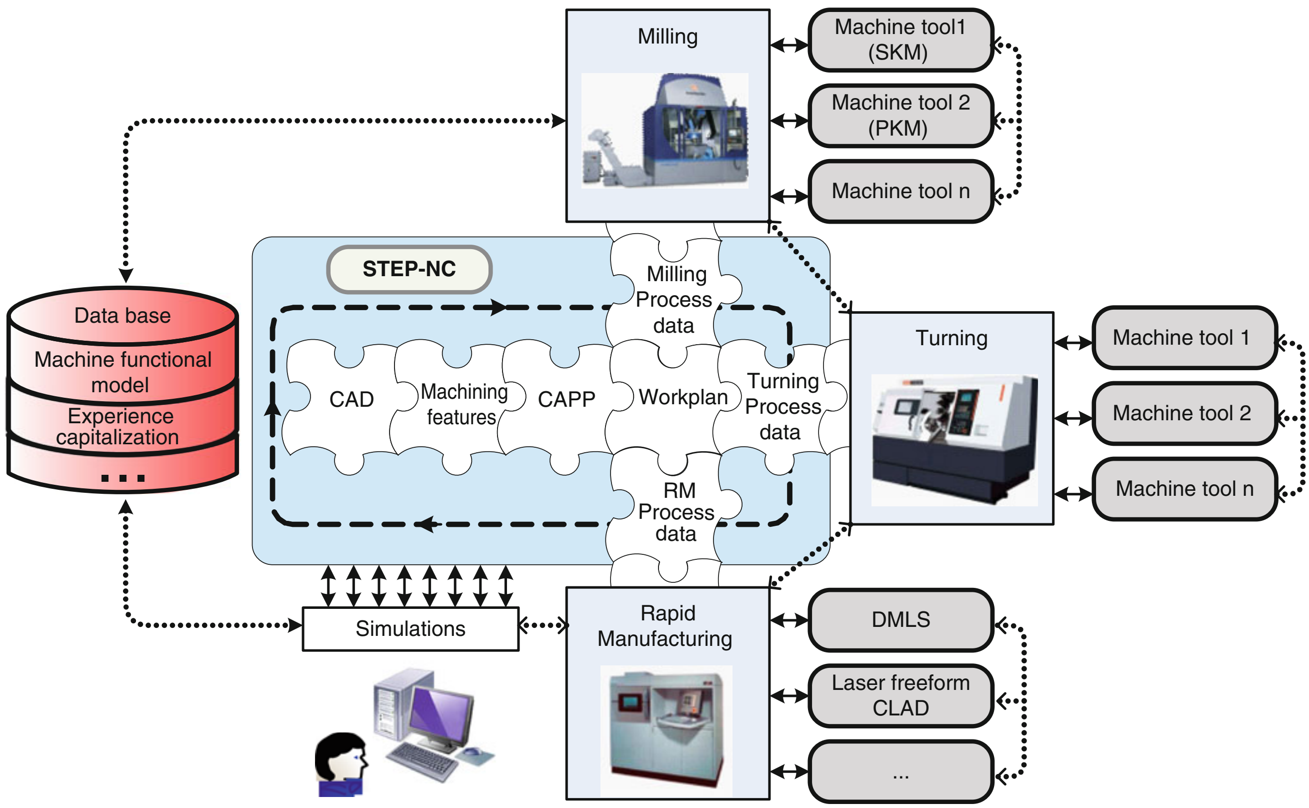

Fig. 1 STEP-NC multi-process numerical chain

4.3 *Multi-process Optimization with STEP-NC*

Multi-process approach involves complex scenarios and new challenges. STEP-NC provides all the bases to support intelligent multi-process manufacturing. A large part of the intelligence is now to simulate and optimize the STEP-NC data and their interpretation at CNC level. In this large transversal field for actions, it is complex to reach a simulation of all the possibilities offered by the multi-process environment. It is all the more complex to find an optimal solution. The proposed approach aims at modelling simulation fields in a multi-process environment.

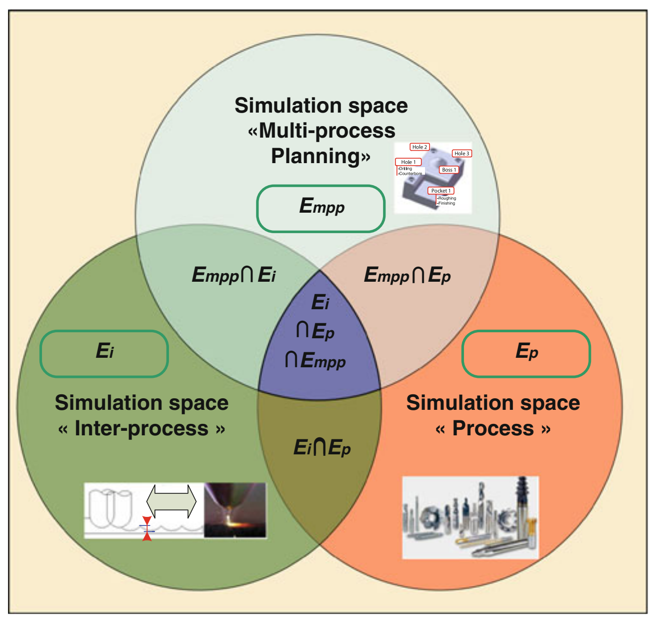

Fig. 2 Simulation in a multi-process environment

5 Multi-Process Simulation Model

5.1 *The Simulation Spaces Concept*

This proposal is based on dividing three main simulation spaces (Fig. 2). A simulation space can be defined as a boundless-but structured-set where simulations can be performed. It is schematized here with imaginary boundaries representing knowledge limits but can be infinitely extended.

These simulation spaces can be distinguished by their respective objectives. They are complementary, interdependent and closely linked.

The main input of the manufacturing numerical chain is the CAD model of the product. This CAD model contains data for part geometry, tolerances, material, etc. These characteristics must be respected and are a theoretical objective for manufacturing process. However, every process has its own requirements that must be taken into account when deciding the manufacturing workplan of the part.

5.1.1 From CAD to AP224 Manufacturing Features and Process Plan: The Multi-process Planning Simulation Space (Empp)

Discretizing a CAD model into manufacturing features means more than recognizing usual geometrical entities. A lot of research works have been done on manufacturing feature extraction [20]. It appears that the solution can hardly be separated from the manufacturing process involved. In other words, the choice of manufacturing feature geometry is linked to a manufacturing process. Thus, a simple part can lead to several feature decompositions depending on the process choice in a multi-process environment, as the process is not fixed. In some cases, an indecison of the suiting process to manufacture an area of the part can lead to further simulations. This is the exploration field for the Multi-process Planning Simulation Space (Empp). The object of Empp is to find the optimal machining features and process plan.

5.1.2 Process Simulation Space (Ep)

The workplan is composed of several workingsteps associated with the manufacturing features. The process simulation space (Ep) gathers all the computations and choices concerning process data and machining parameters selection. Ep is involved for high level manufacturing data selection in STEP-NC file but also integrates shop-floor simulation in the interpreter. This shop floor simulation can be performed offline or online. Typically, an offline simulation will be privileged in the STEP-NC interpreter for tool paths programming, tool paths optimizations, machining parameters adaptation, etc. Real time optimizations, simulations from sensors feedback in the CNC are to be done online and are part of Ep.

5.1.3 Inter-process Simulation Space (Ei)

Relations between processes take a central position in a totally integrated multi-process context. The Inter-process relations and optimizations are fully integrated in the numerical chain with a large consideration of the Inter-process simulation space (Ei), which is new here. In the traditional G-code based numerical chain, a large part of the simulations concern the process (Ep), manufacturing experts choose the well adapted workplan based on their experience and knowledge (Empp), but inter-process simulation (Ei) is hardly possible due to different data standards and expert communication languages.

In the STEP-NC numerical chain, Ei is the missing link between Empp and Ep when several processes are required.

Relations and communication channels between the different processes are enabled with a direct effect on the machining features, the workplan and the process data.

5.2 Simulation Spaces Interactions

5.2.1 Process and Process Planning Interaction

The intersection between Empp and Ep spaces is the place for process simulations in close link with process planning, and reciprocally. Empp∩Ep includes bidirectional relations between CAPP and each selected process. For example, in pocket milling, the tool diameter is limited by the corner radius for finishing operations. On the other way around, process characteristics lead to select a feature rather than another. For instance, using a step drill to machine a hole and the associated counter bore results in forcing the two features to be merged in one workingstep.

5.2.2 Process Planning and Inter-process Relations Interaction

The constraints of each process must be taken into account when creating machining features and workplan. These interactions are simulated in Ep∩Ei. For example, the thermal effects of Direct Laser Manufacturing (DLM) with powder injection [21] constrain the selected features to be manufactured very early in the workplan, before the finishing operations of high speed milling. Reciprocally, machining features sometimes constrain the choice of the process sequence and consequently of the inter-process relations. For example, if a flat must be milled after a turning operation, inter-process interactions are ordered by process planning.

5.2.3 Process and Inter-process Interaction

The process simulation space Ep, directly linked with the machine tool functional model, can provide the simulation results associated with a selected process. The results can have consequences on the other processes machining parameters. For example, the finishing cutting conditions in milling

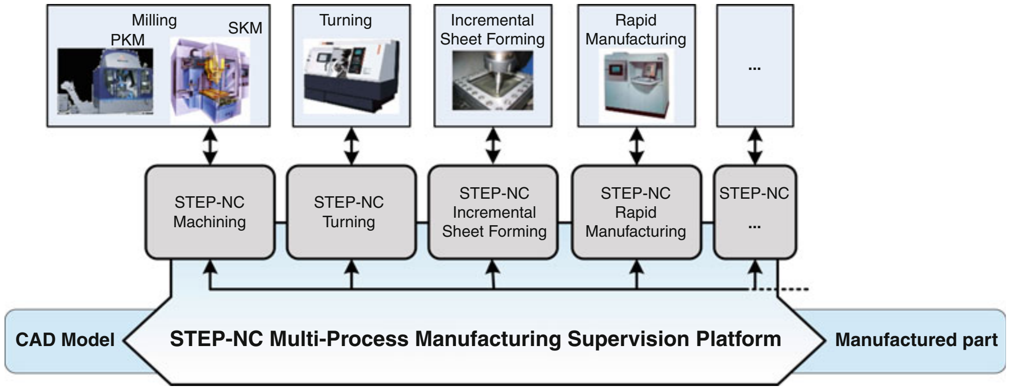

Fig. 3 STEP-NC multi-process manufacturing concept

process (feedrate, cutting speed, etc.) can be adapted due to thermal effects after DLM machining a feature.

A multidirectional data exchange enables a workingstep associated with a process to be carried out in an intelligent multi-process context, taking other processes into account.

5.2.4 A Global and Optimized Solution in the Comprehensive Empp∩Ep∩Ei Simulation Space

The goal to reach is the simulation of a totally integrated manufacturing environment that considers in the same time relevant multi-process planning, inter-process relations and process attributes simulations. However, simulation in Empp∩Ep∩Ei involves complex reasoning and simulation methods. Processing the three presented simulation spaces in the same time is certainly not the best way to initiate a solution. In this chapter, the bases for a discretization of the simulation space are presented. The objective is to help the different expert along the numerical chain to make their choices, not only by considering their own specific area but by integrating the requirements of the whole manufacturing numerical chain. This is made possible by the use of a data exchange standard supporting multi-process planning information and process data.

To validate the main principles involved in multi-process manufacturing, a STEP-NC platform has been developed.

6 Multi-Process Integrated Platform

6.1 STEP-NC Multi-process Manufacturing Concept

To implement and validate the proposal of an integrated multi-process STEP-NC numerical chain, a comprehensive multi-process supervision platform is proposed, in which the digital model of the part can include cross interactions between the different processes (Fig. 3). CNC based manufacturing processes such as milling, turning, rapid manufacturing (DLM for example) and incremental sheet forming are well adapted to be integrated in a comprehensive STEP-NC manufacturing environment. However, very few CNC controllers are able to read STEP-NC files today. Some specific STEP-NC interpreters were developed, mostly as development tools for laboratory applications. They are reviewed by Xu et al. in [22]. Recent works at IRCCyN on high level STEP-NC tool path programming lead to develop a first basic version of an STEP-NC interpreter, dedicated to industrial machine tools [23]. These first concrete works on STEP-NC standard showed the real necessity of a STEP-NC development platform to validate and demonstrate the new programming approaches. Then, a first version of a STEP-NC enabled industrial CNC was developed. It was presented in the frame of the participation of IRCCyN to the normative ISO TC184/SC1/WG7 working group of STEP-NC ISO 14649 standard [24]. This STEP-NC Platform for Advanced and Intelligent Manufacturing (SPAIM) is now under implementation for multi-process machining supervision.

From a conceptual point ot view, SPAIM is an illustration of a global approach aiming to transfer intelligence and decision making into the CNC controller by redefining the CAD/CAM/CNC data chain. This concept is called eXtended CNC (XCNC) and is illustrated on Fig. 4.

6.2 Presentation of SPAIM

STEP-NC Platform for Advanced and Intelligent Manufacturing (SPAIM) is composed of a human/machine interface and several computation modules for translating STEP-NC data into an explicit workplan and tool paths for

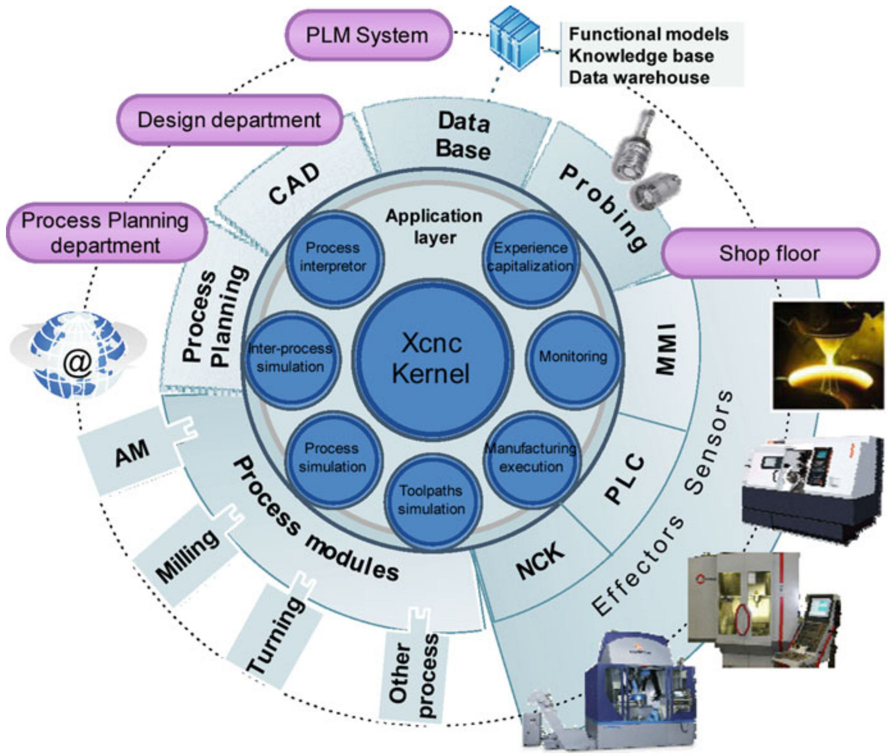

Fig. 4 An overview of the eXtended CNC (XCNC) concept

Fig. 5 SPAIM platform at IRCCyN

each operation [25]. SPAIM has already been implemented and validated on a HSM machine tool of the laboratory [26]. This machine was designed by the Fatronik Company and is called VERNE [27]. It has parallel kinematics architecture and is equipped with a Siemens Sinumerik 840D NC controller (Fig. 5). Another version of SPAIM has been developed for a Hermle C30U high speed machining centre equipped with a Heidenhain CNC controller.

6.3 Multi-process Manufacturing and Simulation in SPAIM

To achieve intelligent multi-process manufacturing in a STEP-NC numerical chain, it is proposed here to use a three level method.

6.3.1 First Level: A Multi-process Manufacturing Platform

The first level consists in developing a multi-process integrated manufacturing platform able to read multi-process STEP-NC file and execute it on machine tools (Fig. 6).

The current developments aim to extend SPAIM capabilities to other processes. Turning applications are developed based on the already existing architecture of SPAIM platform and will allow to machine parts from a STEP-NC file on turning machine tools. Recent works also focus on rapid manufacturing (RM) parts, with new features definitions. RM involves a new way of building tool paths for material adding processes. These works open the way for multi-process manufacturing in a totally integrated STEP-NC platform.

Figure 7 shows the first results of multi-process manufacturing by using SPAIM. Test part 1 is manufactured from

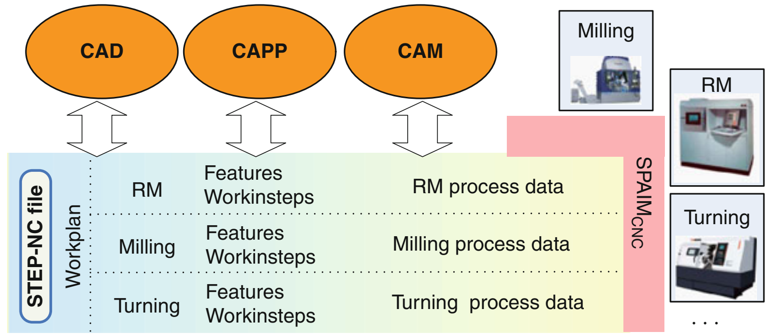

Fig. 6 $SPAIM_{CNC}$: A multi-process STEP-NC enabled CNC

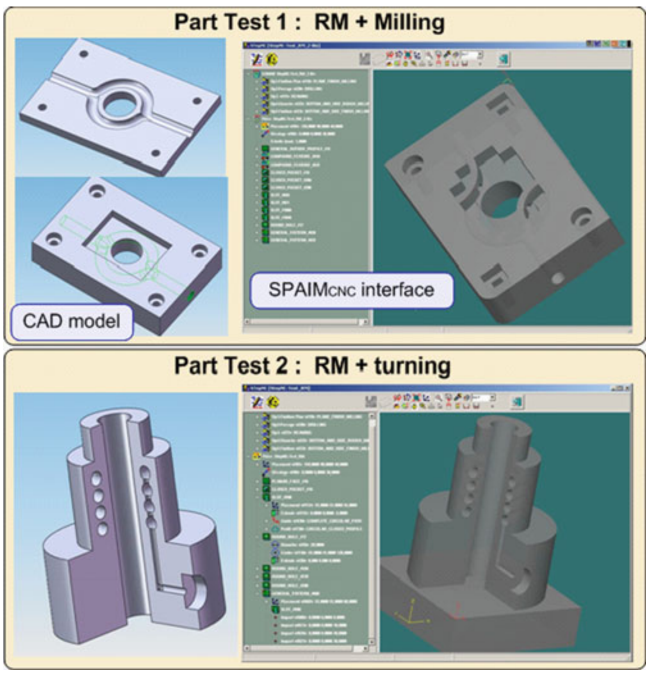

Fig. 7 Multi-process manufacturing parts processed in $SPAIM_{CNC}$

the STEP-NC file by first using RM because of its conforming canal. The finishing of the upper plan, holes and pocket involves HSM. Test part 2 is machined using a RM process and then turning.

In its current version, SPAIM works as a STEP-NC enabled CNC controller ($SPAIM_{CNC}$) which processes workplans made of multi-process workingsteps. Works are lead to develop it as a totally integrated manufacturing platform for multi-process supervision.

6.3.2 Second Level: Integration of Simulation Modules

The second level consists in integrating simulation tools for multi-process planning and process simulations (Fig. 8).

Today, several process simulation tools are ready to be implemented. The next two examples illustrate the use of simulation tools for milling applications.

In the first example, a real feed rate simulation module and a tool deflection compensation module can be added according to works already done at IRCCyN on 3D solid simulation [28] and tool deflection compensation [29]. These simulations associate cutting tools and machine tools functional models to benefit from the most accurate image of the real machining. These simulations can be performed offline for choosing well adapted process data in the STEP-NC file. They can also be performed in $SPAIM_{CNC}$ controller for a machining operation (for example after on-machine inspection). The simulated machining parameters or tool paths will enable to avoid tracking errors and to compensate tool deflection during the real machining operation.

In another example, real time optimizations can also be performed by using process data feedback in the CNC controller. The ICAM (Intelligent Computer Aided Manufacturing) concept is a method to optimize the machining parameters and tool paths by using the available data in the CNC [30] to control the process. A previous application of this approach enabled real time feed rate optimization based on cutting forces estimation from the NC controller data (motors amperage, delivered power, articular coordinates of the joints, etc.). In another application, tool paths are regenerated after online machine inspection. The presented tools are examples of the process simulation capabilities in SPAIM ($SPAIM_{SIM}$).

6.3.3 Third Step: An Intelligent STEP-NC Multi-process Supervision Platform

The third level consists in integrating a new layer for inter-process simulation (Fig. 9). This will stands as a link between multi-process planning and process simulation for an intelligent supervision of the manufacturing processes.

As $SPAIM_{CNC}$ enables CNC to read and interpret multi-process STEP-NC files, $SPAIM_{SIM}$ will integrate simulation tools including inter-process simulation. This is made possible thanks to the large range of high level data available in the STEP-NC file for all the processes involved in the workplan. Cross interactions between the different processes

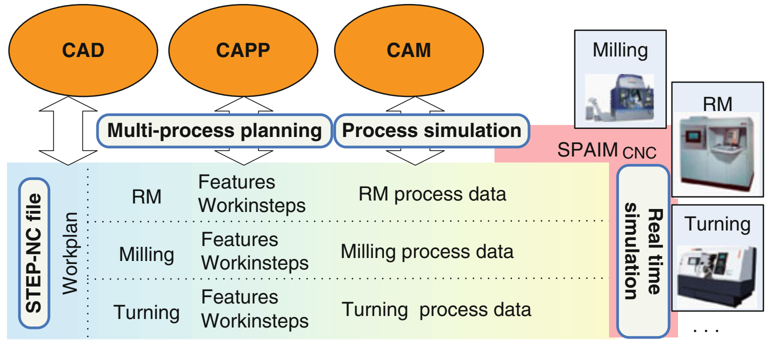

Fig. 8 Simulation modules in SPAIM numerical chain

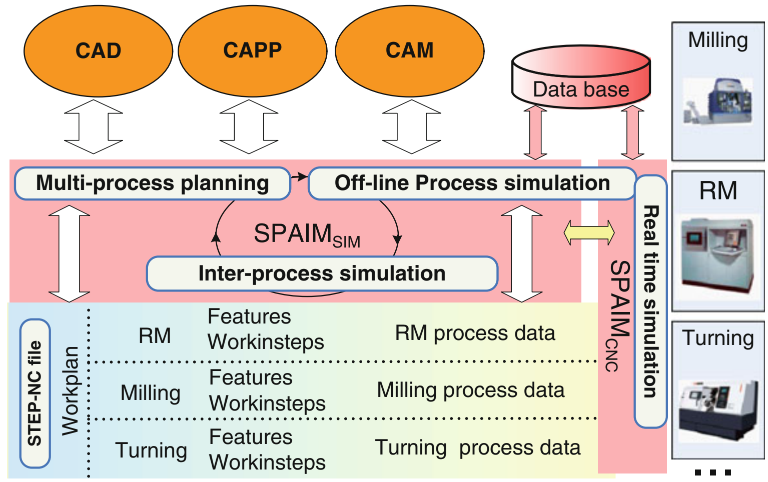

Fig. 9 SPAIM multi-process supervision

will be possible by integrating the associated requirements in the workplan or for process data choice. A database will gather manufacturing data warehouse and knowledgebase. $\text{SPAIM}_{\text{SIM}}$ and $\text{SPAIM}_{\text{CNC}}$ will merge to develop an intelligent and advanced STEP-NC multi-process supervision platform. Further works will lead to develop the multi-process supervision $\text{SPAIM}_{\text{SIM}}$ but needs time to be implemented for concrete validation.

6.4 Applications: Modules Implemented in SPAIM

Figure 10 shows an overview of the structure and modules available in the extended manufacturing integrated system of SPAIM platform.

SPAIM input data is a CAD file (STEP, but other CAD data exchange standards are allowed as IGES, Parasolid, etc.).

In the Planning Unit (PU), features geometry and workplan are generated after process choice, feature recognition and inter-process interaction simulation. Simulation tools for inter-process interaction and optimal process choice are used based on existing works at IRCCyN. Requirements for machine facilities can be added to the generic STEP-NC file.

7 Conclusion

The STEP-NC standard presents a range of new possibilities for intelligent manufacturing. This object oriented standard is well adapted for exchanging high level manufacturing data. It provides a new vision of the numerical chain with multidirectional exchange possibilities. In this chapter, the STEP-NC multi-process manufacturing concept is presented. Multi-process manufacturing associates the advantages of several processes to increase productivity, possibilities for part manufacturing and interoperability but often leads to complex scenarios. In this context, simulation tasks take a central part for intelligent supervision. Thus, the simulation spaces concept is introduced as a performing approach to model simulations fields for multi-process manufacturing. A STEP-NC enabled platform for milling, turning and rapid manufacturing has been developed. This STEP-NC Platform for Advanced and Intelligent Manufacturing (SPAIM) aims at validating the new concepts involved in STEP-NC multi-process manufacturing. Test parts are presented as well. This new multi-process manufacturing approach needs a high level data standard, such as STEP-NC, to be efficiently implemented at large scale. Indeed, the technological improvements conveyed by STEP-NC appear to be obvious

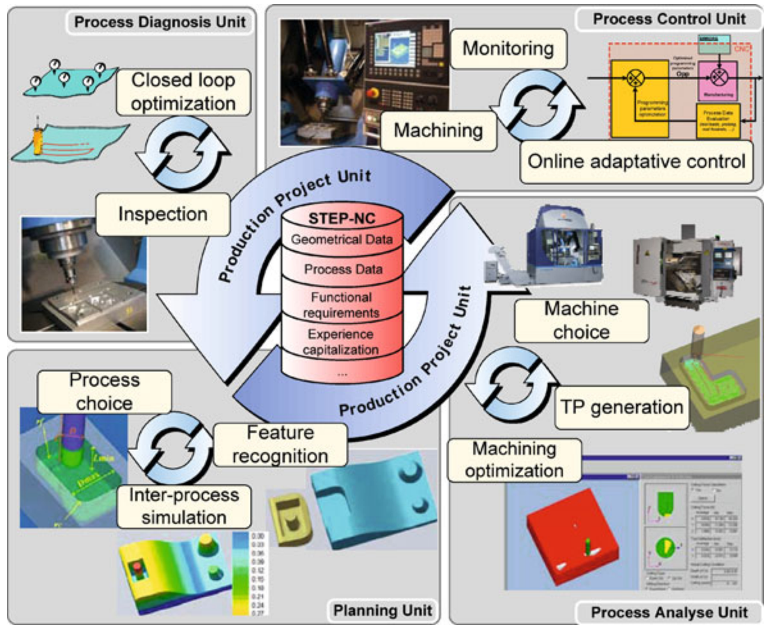

Fig. 10 Main modules implemented in SPAIM

when carrying out innovative manufacturing approaches such as those proposed here. The purpose of STEP-NC is not only to overtake the deep-rooted G-code programming for usual machining operations, but to develop a new intelligent, integrated and interoperable manufacturing environment.

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DFM Synthesis Approach Based on Product-Process Interface Modelling: Application to the Peen Forming Process

J. Elgueder, L. Roucoules, E. Rouhaud, and F. Cochennec

Abstract Engineering design approach are currently CAD-centred design process. Manufacturing information is selected and assessed very late in the design process and above all as a reactive task instead of being proactive to lead the design choices. DFM approaches are therefore assessment methods that compare several design alternatives and not real design approaches at all. Main added value of this research work concerns the use of a product-process interface model to jointly manage both the product and the manufacturing data in a proactive DFM way. The DFM synthesis approach and the interface model are presented via the description of the DFM software platform.

Keywords Product-process interface · DFM · Virtual prototyping · Manufacturing process selection Manufacturing data management · Peen forming

1 Introduction

For almost 30 years CAD systems have been developed and improved to currently provide very powerful features to support product's forms modelling. PLM approaches and systems have also been highly developed for the last decade to manage the entire product lifecycle information. Nevertheless CAD and PLM systems are currently used the central systems that make the design process a geometric-centred process. CAD model is indeed very often proposed by one person and is used as an input for product analyses (CAM, FEA…). The design experts therefore react and ask for changes that are propagated according to several relations either in the CAD or the PLM model. The design process is then a "redo until right" process.

The paper aims at presenting a design approach based on a DFM synthesis by least commitment[1] process. This approach provides a more proactive position of each design expert (particularly manufacturing) involved in the design process in order to set the CAD model as the result of a collaborative decision making process. The design is then based on a "right the first time" process. This approach is based on a product-process interface modelling implemented in a laboratory-made DFM_Synthesis software. The process planning expert is then really seen as a designer (see Sect. 5.2.2).

The global context of IT (CAD and PLM) supported design activity is given in Sect. 2.

Afterward, Sects. 3 and 4 give details of specific issues and introduce the DFM approach proposal. Specific breakthroughs are written regarding the design process and the product modelling.

The following Sect. 5 focuses on managing manufacturing information based on the product-process interface. This manufacturing information is definitely linked to product data in order to address CAD modelling and product behaviour and manufacturing simulation according to the selected process plan. The DFM_Synthesis software architecture is illustrated in an example of the aeronautic industry (called Wing Cover in the following text).

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[1] "Least commitment" has to be understood as "including as less design constraints as possible". CAD model is indeed currently defined thinking of the entire lifecycle (ex. manufacturing, assembly…) but this information is not really explicit in CAD product breakdown. The CAD model is then very often over constrained without any explicit design rationale. The paper focuses on the energetic and manufacturing rationale integrated in design.

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Finally the conclusion and the perspectives for further work are given.

2 Overview of Information Systems in a Current Industrial Context

Most of CAD systems (ex. CATIA, Pro-Engineer, solidworks . . .) currently provide very interesting B-Rep or CGS based algorithms to create forms as edges, wires, faces, shells or solids, to seek those form features (ex. topological explorer, . . .) and to change those forms (ex. draft angle, radius. . .). PLM solutions have also been developed to provide advanced functions for information management (ex. files versioning, files maturity, files access rights. . .) even if they are only able to manage persistent files and not the given specific data contained in it.

This design approach based on PLM and CAD systems has shown its great interest in industry to link specific information (i.e. analysis) to a unique geometrical kernel. Figure 1 shows some of those links (ex. CAD-CAM, CAD-FEA). It is therefore possible to propagate the impact of form features modifications to the analyses whenever in the product development process. Actually, this propagation is really effective in specific "integrated" software during the embodiment and detail design phases and. The problem is still open in the requirements specification and conceptual phases.

3 PLM and CAD-Centred Design Process Issues

3.1 Engineering Design Process

While CAD and PLM solutions are providing very good supports for information management [1], new design methods and theories have been proposed in the last 15 years as explained in a recent sate of the arts [2].

The first phases of design (requirements specification, conceptual and embodiment design) aims at assessing requirements and functions in order to define the product structure breakdown and the associated CAD models (parts and assembly CAD models). In those phases of design, the process is based on some fundamental concepts such as FBS [3] and sometime axiomatic design [4] when the solution tends to provide independent relation among functional and structural parameters. Afterwards (cf. Fig. 1), the detail design phase (CAM, FEA. . .) other "designers" are assessing this first solution and react by giving some new recommendations (i.e. information integration) for improving the design solution. A lot of collaborative decision-making processes are then beginning to finally converge to a common agreement.

A lot of interesting concepts with respect to integrated design [5, 6] and advanced product modelling [7, 8] have also provided real advances in design methodology and information modelling. They give opportunity to really set relations as soon as possible among the whole product information related to its entire lifecycle. Nevertheless the process is still based on a "redo until right" action and those concepts could have even more benefits through tackling the following issues[2]:

1. How to integrate detail design information by least commitment on a "partially" defined CAD model in order to be more proactive (vs. reactive).
2. How to work with multiple-CAD models in order to really have multiple solutions with respect to every expert's design intents (manufacturing intent, assembly intent. . .); instead of a unique central CAD model which is the support of the decision making process.

Point 2 has already been introduced in [9] and nevertheless should be discussed in more detail in the future. The present paper only focuses on points 1 which has also been discussed in some references that give the fundamental concepts of the research work:

- Form features can be generated from detailed FBS information modelled in multiple-perspectives product modelling. It is then very useful to understand the mapping between product's functions and form features [10].
- That approach by least commitment is interesting to foster innovation coming from every expert involved in the design process and not only the "designer" that creates the CAD model [11, 12].

The key issues treated in this chapter are the follow up to those references dealt in point 1. The objective is to provide a DFM approach to support manufacturing information synthesis in the design phase. That information is then used to generate part of the product CAD model.

3.2 Design for Manufacturing Approach and Design Synthesis Proposal

In most of papers on Design For Manufacturing [13, 14], the objective was to compare several design solutions with respect to various technical or economical criteria. Those results are very interesting to give a global "cost" seen as a weighted global equation to find the "best" solution

[2] Those issues are obviously not exhaustive. They are the ones currently treated by the authors.

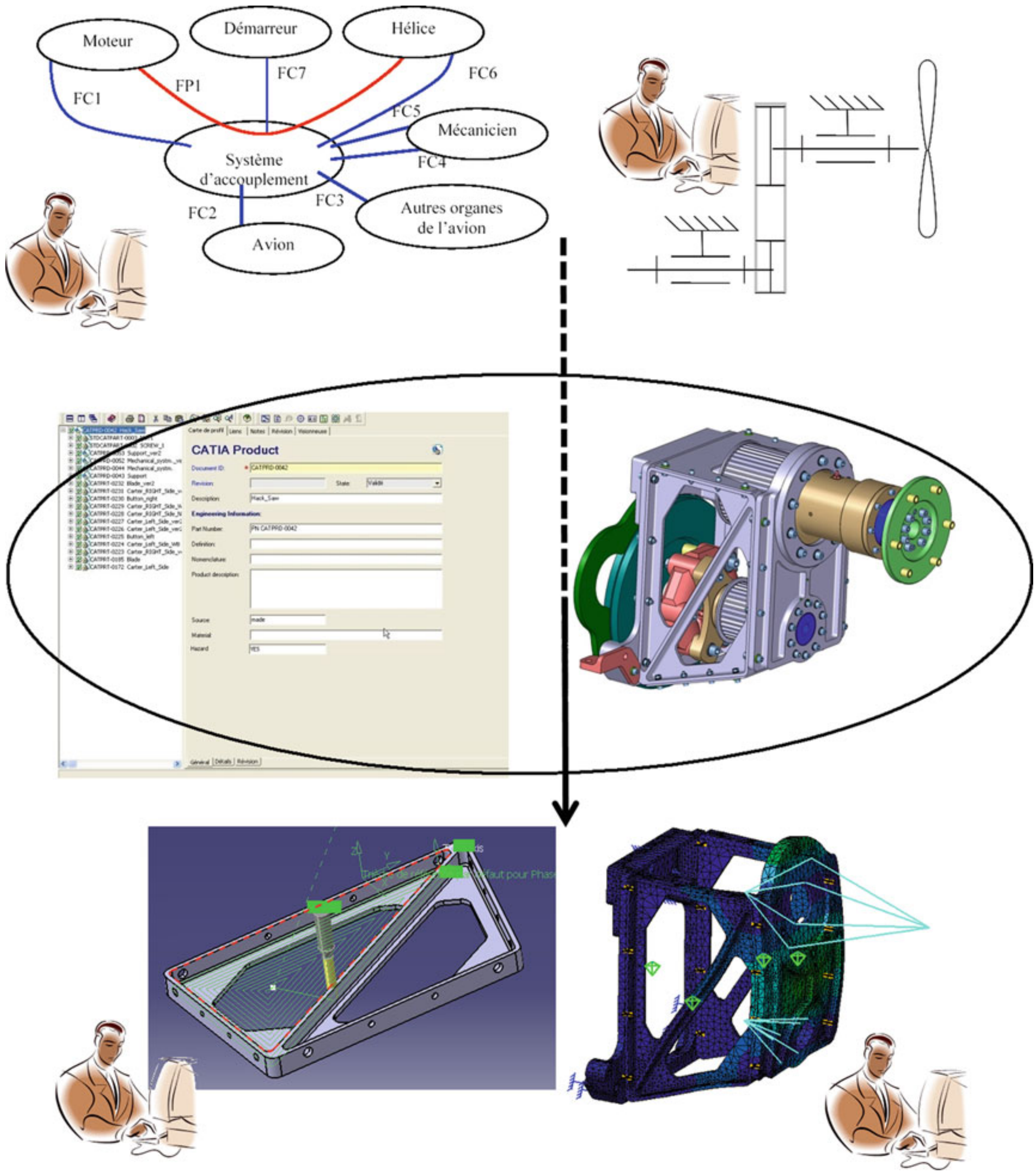


Fig. 1 Current engineering design process taking into account advanced design concepts (collaboration, integration, PLM...) of the state of the arts

(Fig. 2). Manufacturing information based on rules or guidelines are then given in order to know how the product could be changed to reach a lower "cost".

3.2.1 Manufacturing Information: Identification vs. Integration

As far as manufacturing information is concerned, the DFM approach has to be based on product-process relationships (ID) that aim at linking a vector of product parameters (PD) and a vector of process parameters (PF).

$$\{PDi\} = [IDij] \times \{PFj\}$$

It is nevertheless important to distinguish:

- Identification approaches that aims at modelling the relationships matrix ID. The literature provides a lot of results of identification related to specific manufacturing processes (ex. [15]).

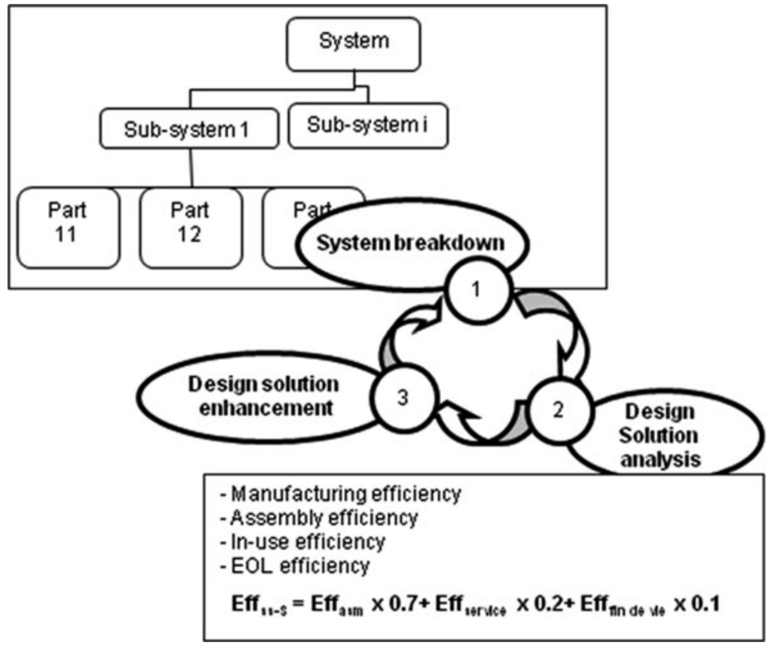


Fig. 2 Example of global efficiency assessment in DFX approaches

- Integration approaches that aims at using the relationships for information synthesis in design. The main added value of the proposed DFM approach is actually to identify {PD} vector with respect to the choice of {PF} vector.

Since this research work is part of a larger project regarding fatigue analysis of the designed component the authors actually state that product vector {PD} is composed of four parameters:

- Dimensional tolerancing
- Form quality
- Roughness
- Residual stress field

Obviously, other parameters also impact the fatigue behaviour (ex. micro-structural effect, micro-cracking, voids. . .) and should be treated in the future. Authors started by studying residual stresses as it is the main parameters involved in peen forming process.

Concerning manufacturing vector {PF}, parameters are depending on the selected manufacturing processes. This chapter will present the model of the product-process database in which those parameters are defined and on which the ID matrix is based. Authors then assume the existence of such database since references have already presented ways to identify the ID matrix [16].

3.2.2 Breakthrough of the DFM Synthesis Proposal

As presented in Sect. 3.1, authors clearly assume that currently CAD modelling is then realised by practising designers thinking of manufacturing as any other information (ex. Assembly, recycling. . .). It is nevertheless modified in a “redo until right” process once manufacturing simulation is done because of some aspects of the model that could be inappropriate for the process.

The breakthrough of the proposal lies on the comodelling of Manufacturing plan and CAD model. It then provides a real information support to “think of manufacturing” in design. That means manufacturing activities have to be assessed concurrently to the product development and the CAD modelling activity. This is totally in coherence with computational synthesis methods as defined in [17].

This chapter therefore presents an original DFM Synthesis approach for manufacturing information synthesis in design. The originality is related to the proactive and by least commitment characteristic of the DFM method. It gives some results to manage the data of the whole manufacturing process plan and to integrate those data (i.e. knowledge synthesis approach) to generate the CAD model.

The CAD model and process parameters are then jointly defined that totally fits with concurrent and integrated design concepts.

The main advantages of that design approach are detailed in the following section considering the fact that:

- The CAD model is defined taking into account manufacturing information.
- The manufacturing simulations do take into account the history of the whole process plan. Since the CAD model is the input of the simulation, it has not to be seen as virgin

of any previous manufacturing operation. On the contrary it has to embed manufacturing parameters and product-process relationships.

4 Fundaments of the DFM Synthesis Approach

The developed model of integration (i.e. product-process interface model) is based on the research work done by Roucoules and Skander [18]. They showed that taking manufacturing information into account as soon as possible in the design process is of great interest for manufacturing process selection. That indeed supports the emergence of product geometry [9] and goes towards a limited number of iterations between design and manufacturing decisions; the term "right the first time" is used for such approaches versus the approaches "do until right".

Considering that the manufacturing domain can be extended to other product lifecycle phases (e.g. assembly, recycling, dismantling, etc.), the assumption is that the design process should then be centred on multiple-views product modelling and expert analyses instead of being CAD-centred. One of the main limits of that CAD-centred approach remains in the unique product breakdown that does not reflect the design intentions of every expert designers involved in the design group. Figure 3 shows the form features breakdown used to obtain the CAD model of a Wing Cover. Obviously, this breakdown gives the way to draw the entire form but does not represent what should or could be the real manufacturing process plan. It does not make any sense for the engineers in charge of the manufacturing activities. For instance, the three slots are designed using the "extrusion" feature based on a 2D sketch while they should be manufactured as three machining operations. The information structure should therefore include both the manufacturing and form breakdowns (i.e. multiple-views).

4.1 Design Process by Least Commitment

Product design process usually starts with functional analysis and goes quite quickly to CAD modelling. This CAD model is defining the topological information on the product but this information is very often defined without "thinking" of the manufacturing plan. Moreover, CAD model does not embed tolerancing, roughness... of the product at all.

That limit seems obvious since manufacturing processes are not yet selected. Manufacturing information can then be integrated only after the manufacturing process is selected.

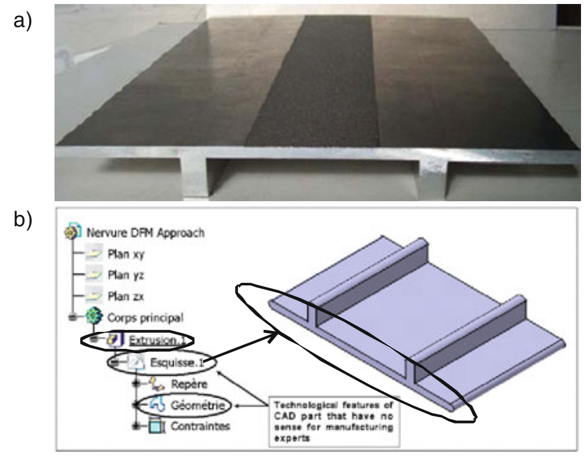


Fig. 3 (**a**) Physical wing cover – (**b**) Incoherency between CAD model breakdown and manufacturing plan

4.1.1 Functional Specifications Modelling

Nevertheless, a better design process would be to select a manufacturing process earlier and to integrate manufacturing information straight to the right product breakdown. In order to know when the manufacturing process selection can be achieved, the authors propose to model the DFM process (cf. Fig. 4) and to really look for manufacturing functions identification. Those functions are seen as specific required energetic surfaces (i.e. skins) connected by specific energetic skeletons. For further details, this Skin and skeleton model is fully detailed in [12, 18] and is very similar to the skeleton [19] or "Working Pair Surfaces and Channel" concepts given in [20]. Figure 5 gives the energetic skin and skeleton model concerning the CAD model of the Wing Cover given in Fig. 3. This model is only giving functional information (i.e. least commitment) without assuming what could be the manufacturing process that will be selected by the manufacturing expert.

4.1.2 Manufacturing Process Selection and Information Synthesis

From that usage Skin and Skeleton manufacturing expert can select the more adequate process plan that obviously have to respect the initial energetic specifications. Actually, several manufacturing solutions (i.e. alternatives) can be selected.

Manufacturing skins and skeletons are then used to model the product-process interface and to generate the CAD models (or CAD alternatives) with respect to the process plan alternatives. Once again this CAD model is co-created using manufacturing information synthesis by least commitment (i.e. only with manufacturing constraints and no other constraint at this time).

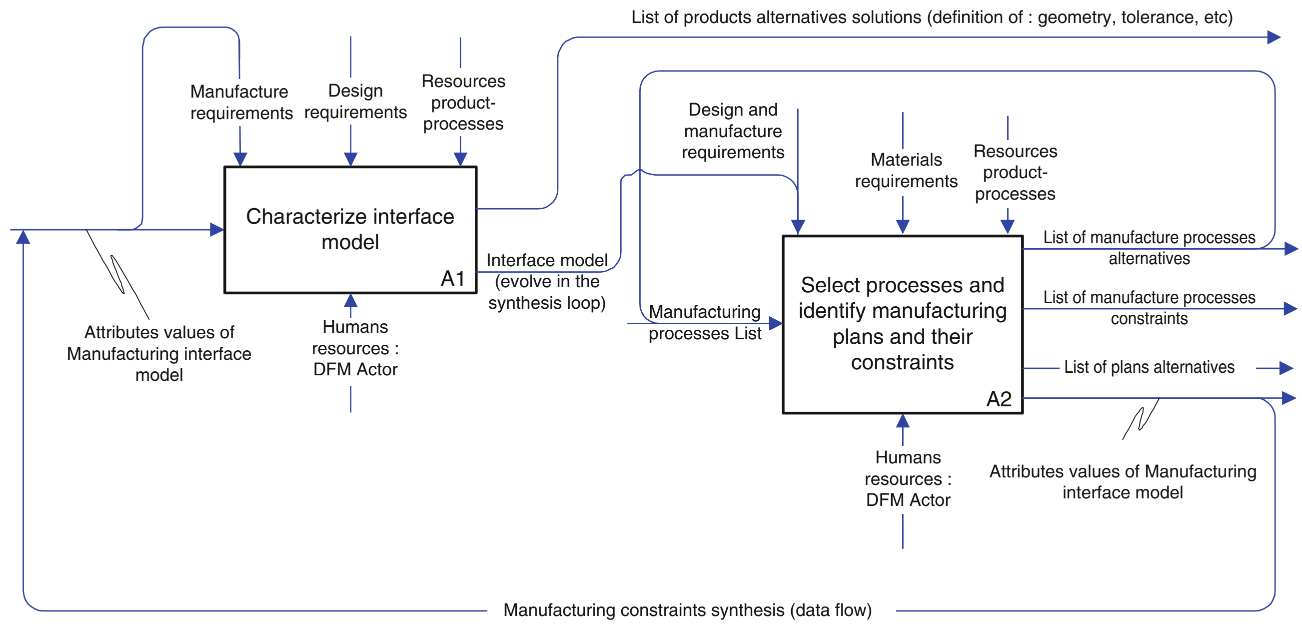
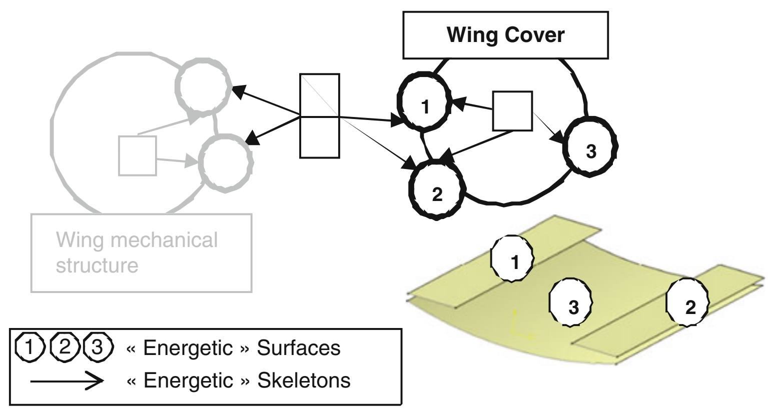


Fig. 4 The DFM activity model

Fig. 5 Energetic skin and skeleton of the Wing Cover and respective form features



5 Product-Process Interface Towards Advanced CAD Modelling Linked to Manufacturing Data Management

This section gives the details of the product-process interface used in a DFM synthesis approach. As already introduced the added value lies in:

- A CAD model created "right the first time" taking into account manufacturing information
- An advanced product-process breakdown to manage manufacturing data on entire manufacturing process plan.

5.1 Product-Process Interface Modelling

The product-process interface model comes from the assumption that every manufacturing operation is based on a material flow called manufacturing skeleton in the following. This flow (or skeleton) (cf. Fig. 6) is then defined with:

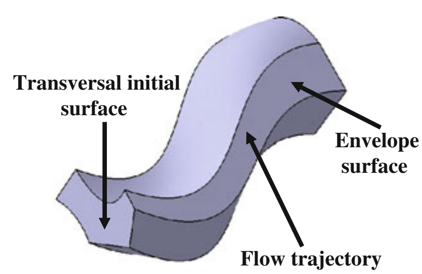


Fig. 6 Material flow (i.e. manufacturing skeleton) definition for product-process interface

- Sections defining the initial and final surfaces through which the material is going (i.e. transversal surfaces).
- A trajectory on which the material is formed.

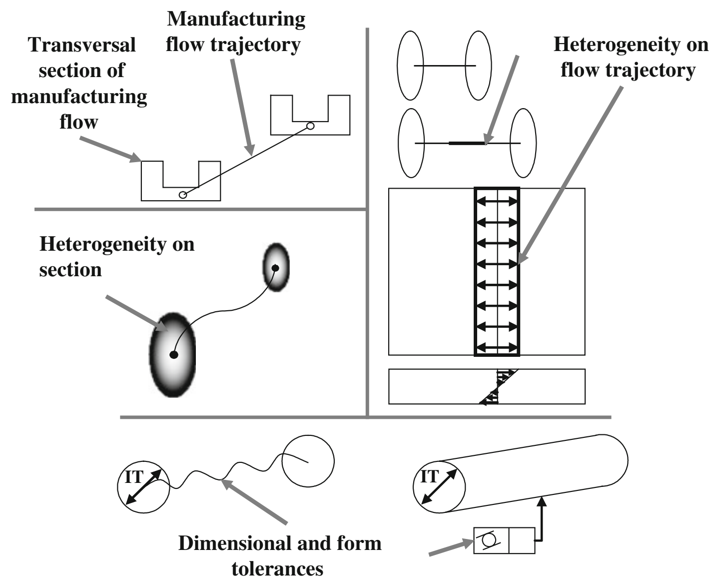


Fig. 7 Example of product information issued from manufacturing process and managed by the product-process interface

- An envelope surface which is generated. The link between envelopes generated in the process plan will provide manufacturing skins.

Based on that flow (called manufacturing skeleton) the material can be added (ex: injection), removed (ex: machining) or deformed (ex: forging, peen forming) to obtain the final part surfaces (called manufacturing skin). In the "added" and "removed" categories those surfaces are equal to the envelope surface.

Beyond very good results presented in [21] which concern the current results of that approach for nominal aspects, Fig. 7 gives the novelties of that paper. The new results concern the capabilities of that product-process interface:

- To manage product tolerances coming from manufacturing operations. Each level of tolerancing features (dimensional tolerances, form tolerances and roughness) is concerned. Figure 7 shows how those features are integrated in the product-process interface (i.e. manufacturing skeleton) characteristics.
- To manage material heterogeneity coming from manufacturing operations. It is also obvious that material flows (cf. above assumption) generate some gradients inside the manufactured product. Those gradients (ex: residual stresses) can, for instance, come from:
  - Thermal phenomena in the skeleton's sections that come from a cooling phase which is not always homogeneous during casting operations.
  - Mechanical deformation on the skeleton's trajectory coming from forming processes (ex: forging, peen forming. . .).

The example of peen forming is given in the following section which is indeed one of the operations used to manufacture the Wing Cover. This example is also very interesting to show the added value of the approach with respect to manufacturing data management (cf. Sect. 5).

5.2 Generation of Advanced CAD Model Based on Product-Process Interface

Keeping in mind both the CAD model presented in Fig. 1 and the "by least commitment" CAD model given in Fig. 5, the generation of an advanced CAD model which takes into account manufacturing plan is presented.

5.2.1 DFM_Synthesis Platform

This generation of the advanced CAD model is currently supported by a DFM_Synthesis platform that can be seen as a KBE application (Fig. 8). The architecture of the software is made of:

- A DFM_sythesis software that manages the product-process breakdown and the form features algorithms that generate the CAD model from manufacturing skeleton. The skin and skeleton data model of the KBE application is currently implemented using Open CASCADE Application Framework (OCAF) encapsulated in Microsoft Foundation Class objects and Open CASCADE geometric algorithms.
- A product-process database that stores information concerning the ID matrix presented in Sect. 3.2.1. This ad-hoc database is so far developed with MS Access. The

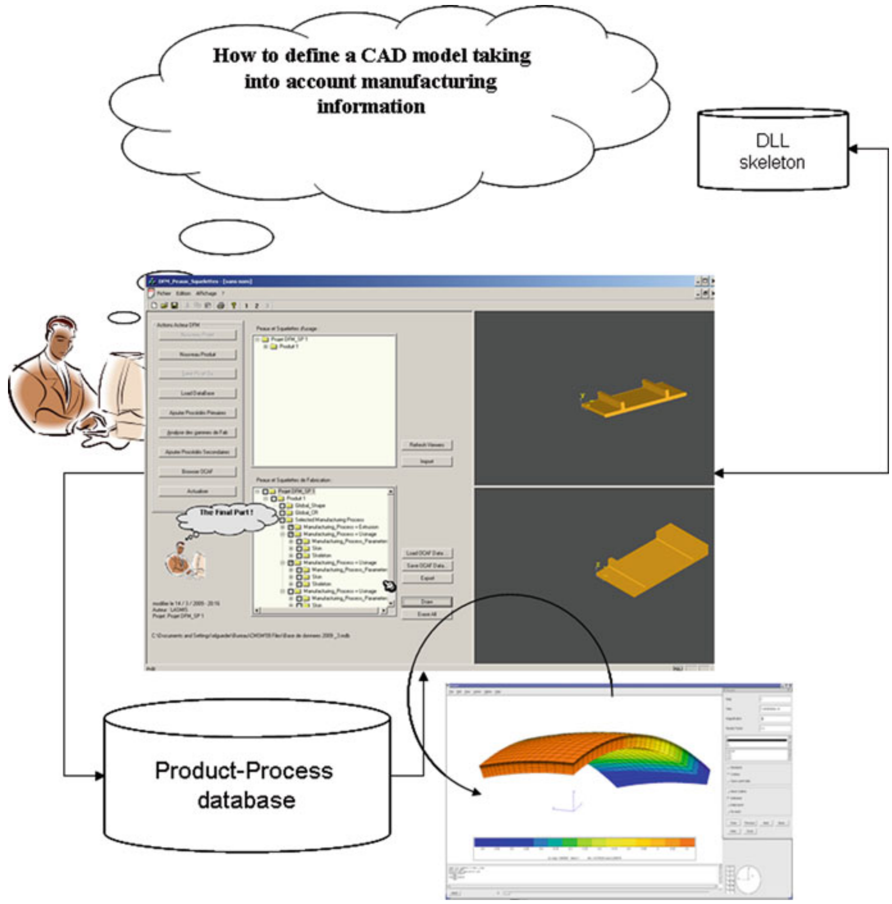


Fig. 8 Overview of the KBE application

identification is assumed, in this chapter, to be already done. Three ways of identification are however treated: analytical models, experimental data, and numerical simulations.

- A Finite Elements Analysis software that is used to assess the product topology (cf. Sect. 5.3.1). Indeed, as previously presented, the product-process interface model manages the heterogeneity coming from manufacturing operation that created residual stresses. Those residual stresses have to be treated at each step of the manufacturing process to calculate the elastic equilibrium of the entire part.

The "designers" is then using the DFM_Synthesis application which sends requests to the database in order to constrain the product parameters variability. The design is done "thinking of" manufacturing.

5.2.2 CAD Model Generation Scenario

Authors fully assume that the DFM_Synthesis scenario is processed by a manufacturing expert. There is no automatic process selection at all. Nevertheless, as already-introduced, the CAD model is co-generated once the process is selected. This manufacturing expert is then seen in this approach as a "designer".

The expert therefore:

- Realises the first mapping between product requirements and manufacturing processes. Shey matrix (cf. Fig. 9) [22] is used to map initial partial CAD model (as presented in Fig. 5) to a manufacturing process list.
- Selects the first primary process from this list.
  - The database therefore returns the process parameters and a list of potential manufacturing skeleton features.
- Selects one of the manufacturing skeletons and gives values to each parameter (i.e. process vector {PF}).
  - The database returns the product values (i.e. product vector {PD}) with respect to [ID] matrix.
  - The open CASCADE algorithms generate the CAD model according to the manufacturing skeleton features.

Figure 10 presents the manufacturing plan with regard to the Wing Cover already shown:

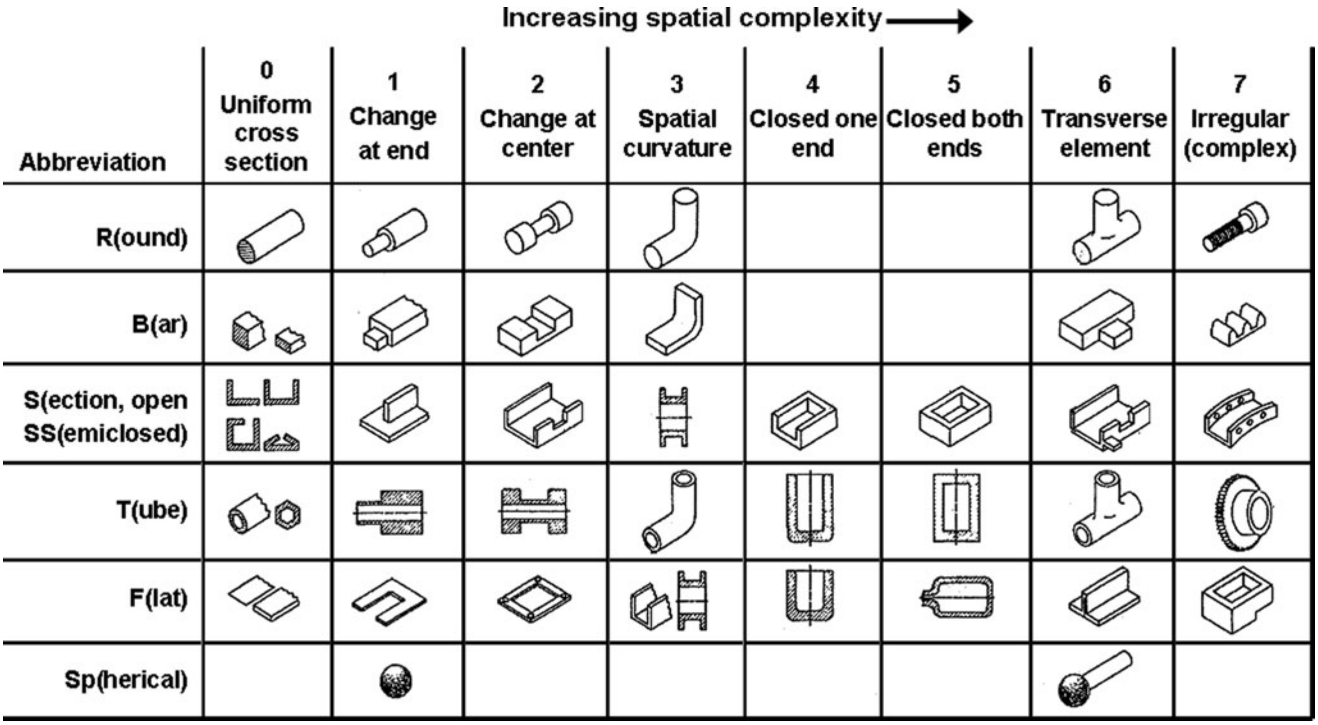


Fig. 9 Shey matrix for form features classification

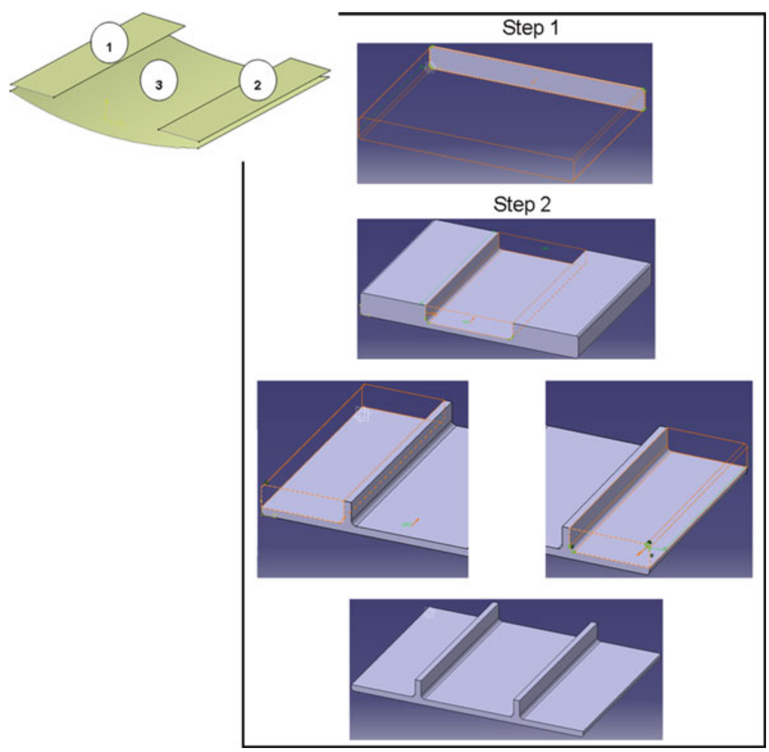
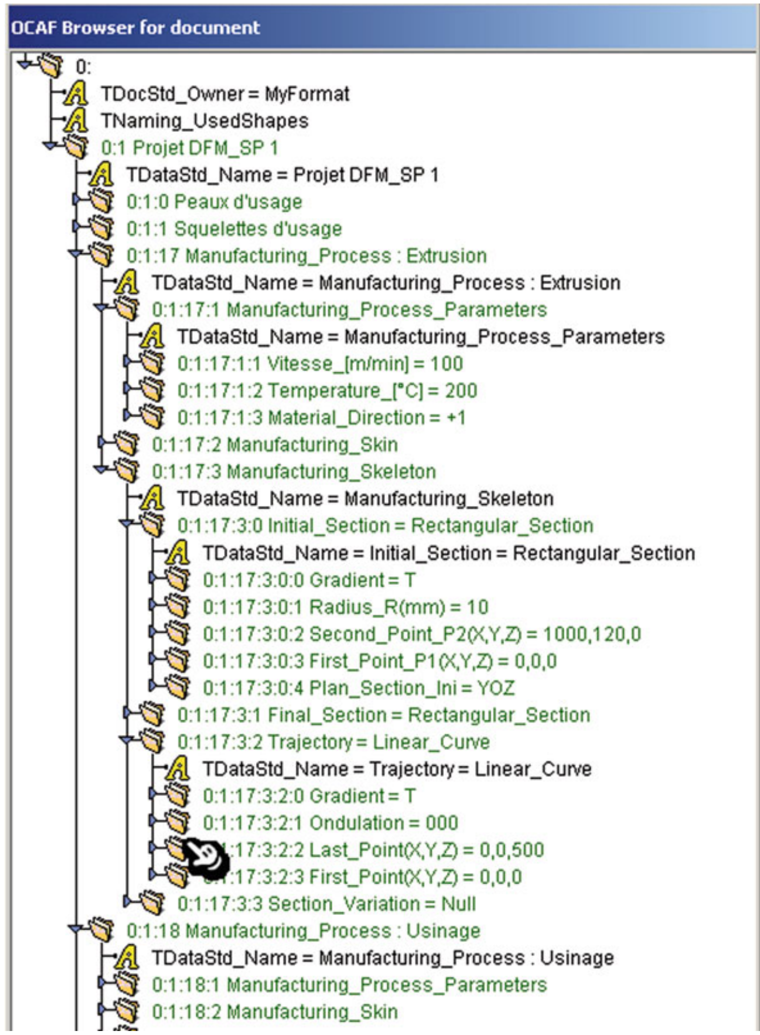


Fig. 10 Illustration of the proposed DFM approach (from initial form feature to a complete CAD model)

- An extrusion operation as primary process. Extrusion tolerances are given by the product-process database and are integrated in the section of the extrusion skeleton that provides extra product information. Radius value of the section are also coming from the database to really take into account manufacturing constraints of the extrusion process (Step 1)
- Three machining operations are then proposed by the manufacturing expert as secondary processes. (Step 2)

Fig. 11 OCAF structure for product and manufacturing process information management (example of the extrusion operation among several alternatives)



So far the final CAD module seems to be equal to a classic CAD model. However, it has been automatically generated while defining manufacturing plan and constraints. That is the main added value of the DFM approach. Other process plan alternatives could have been selected (cf. Fig. 11) that would then have generated other CAD alternatives.

A third peen forming operation is therefore defined and is presented in the following to focus on the residual stress. That is also one of the major issues tackled by the approach in order to link product and process information. This cannot be done using current commercial CAD software.

5.3 Product-Process Interface for Product and Manufacturing Data Management

The final structure breakdown created actually gives every product alternatives according to the manufacturing alternatives (cf. breakdown tree in Fig. 11). The solution is chosen by the manufacturing expert in the KBE application which then provides the respective CAD solution and respective material characteristics.

The evolution of the CAD model according to each manufacturing operation is then managed using the product-process interface. This approach of manufacturing data management is clearly an added-value facing the current commercial CAD software.

5.3.1 Product Behaviour Management

The first interest of managing product-process interface lies in the mechanical analysis of the product. Product behaviour is indeed strongly related to material characteristics that are most often considered as homogeneous in the global volume of the part. Unfortunately, that homogeneity does not exist at all since most of manufacturing processes generate gradients of material characteristics (ex: forging, casting, shot peening, peen forming. . .).

Based on this KBE application it is then possible to know what is the exact initial state of the product (topology, quality, material heterogeneity) regarding each manufacturing operation. This initial state obviously encapsulates the product behaviour issued from previous manufacturing operations. Indeed each manufacturing interface (i.e. manufacturing skeleton) gives that information.

Let us now talk about the Wing Cover part that should actually have a curved surface in order to fit fluid mechanic specifications. It is then possible to create a CAD model with respect to this curved surface but it does not make any sense without thinking of the manufacturing operation that physically generates that deformation. The proposed DFM_Synthesis approach then provides a great benefit for that.

The impact of material change (specifically residual stresses) based on manufacturing processes can be taken into account in the product-process interface (cf. Fig. 12) and automatically processed to calculate the product deformation (cf. Fig. 13). The Finite Element calculation is based on an

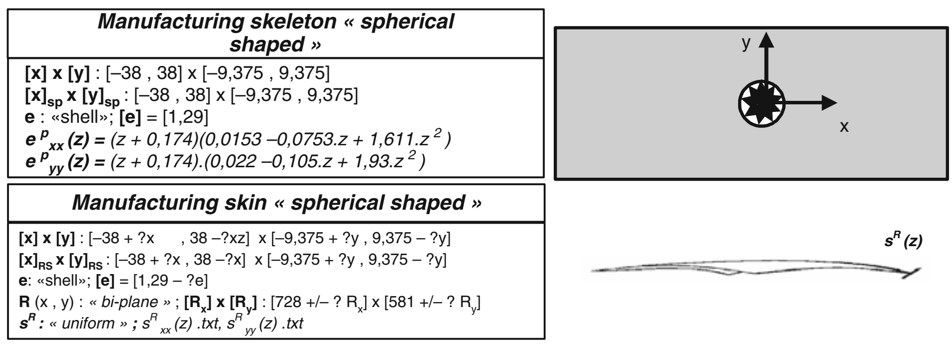


Fig. 12 Illustration of manufacturing skeleton of a peen forming operation to embed residual stresses information

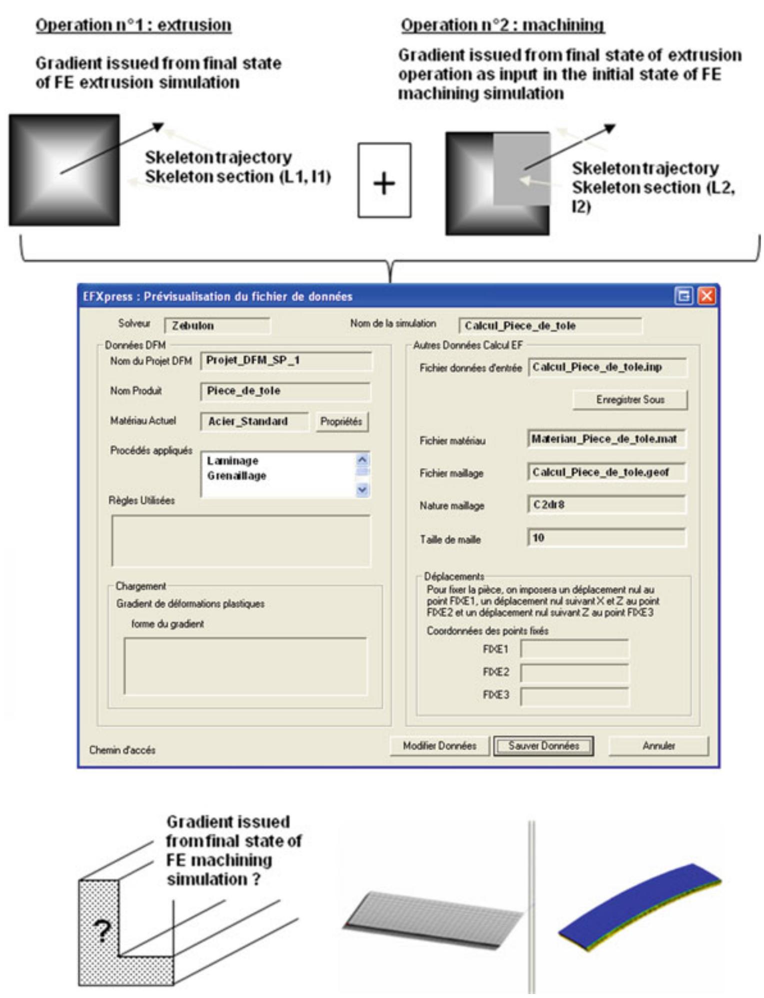


Fig. 13 KBE and data management supporting field transfer for product deformation analysis

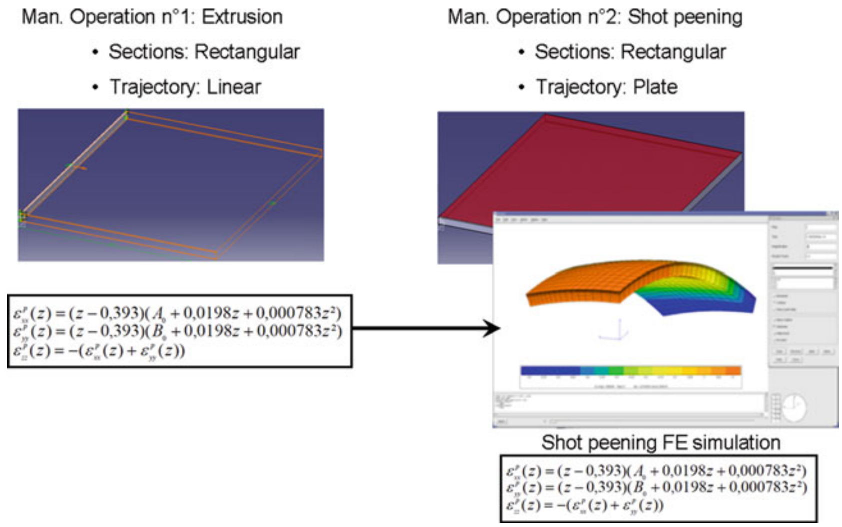


Fig. 14 Illustration of transferring residual stresses embedded in skeleton from first manufacturing simulation to the next one

elastic analysis of the part and the solver has to reach the global equilibrium of the residual stresses in it.

Since the KBE software manage the entire process plan, manufacturing expert acting as a designer can assess the product deformation with respect to each specific manufacturing operation (ex: extrusion, milling, peen forming) or to the entire process plan.

As presented in the Fig. 13, the main difficulty of the calculation currently remains in "summing up" each residual stresses field from every manufacturing operation.

Assuming that meshing is actually only used to solve the Finite Element Analysis, the authors argue the benefit of using the proposed product-process interface (i.e. manufacturing skeleton) to solve that issue. Manufacturing skeletons are, indeed, not based on meshing and the gradient of information can then be linked to the topological parameters that have a strong physical meaning for manufacturing experts. That is not the case of any meshes that are only dedicated to specific simulation models.

Keeping the link between manufacturing parameters and product information is very useful to notify every change concerning product definition. They can therefore be quickly propagated to manufacturing information without processing any new FEA.

The proposed solution based on the presented product-process interface is to link residual stresses field to each manufacturing skeleton. This is represented by topological features linked to manufacturing parameters (cf. Fig. 12); each skeleton being adequate for each material flow of the given manufacturing operation.

Finally, once the entire manufacturing process plan is defined and the respective product information (form + residual stresses field) is generated, all this information can be exchanged with fatigue analysis software; which therefore takes into account the heterogeneity of the part to assess the global product behaviour.

5.3.2 Manufacturing Data Management for Manufacturing Process Simulation

So far we have presented how product-process interface is used in a DFM approach for CAD modelling taking into account information of material heterogeneity (i.e. residual stresses – cf. Fig. 7) to better simulate product deformation according to the process plan.

Manufacturing data management via product-process interface modelling is actually also used to simulate each manufacturing operation (extrusion, milling, peen forming). Once again, process simulations very often assume the initial residual stresses as null whereas it is not the industrial and physical situation.

The proposed product-process interface is then also interesting to "chain" every process simulation. Every simulation can indeed integrate an initial state of residual stresses with respect to the history of previous operations of the process plan (ex: stresses coming from forging, casting. . .).

Figure 14 illustrates how product-process interfaces with respect to former manufacturing operation are used as input information in the following simulation of the peen forming process. The simulation is currently processed with Zebulon as Finite Elements solver.

The first manufacturing operation consists in extruding material that create the parallelepiped CAD model, attached tolerances and residual stresses as previously presented. The second operation is a peen forming operation. The ball impacts all the upper face and generates plastic deformations. This simulation of the peen forming operation solves the elastic spring-back of the entire part and provides the curve part. The final residual stresses gradient is integrated in the manufacturing interface model to be used for potential further manufacturing operations as milling or drilling for instance.

6 Conclusion and Recommendations for Further Work

This chapter presents a product-process interface model for a DFM synthesis approach.

This model based on material flow modelling with respect to skeleton and skin concepts is first used to integrate manufacturing information as soon as possible in the product design process (i.e. "by least commitment design approach"). This integration strongly leads the CAD modelling and by the way centres the design process on expert designers' knowledge and not on form features any more.

The second objective of that interface model is to manage manufacturing information linked to product characteristics (ex: topology, tolerances, residual stresses…). It is then profitable to simulate manufacturing processes taking into account the evolution of the product characteristics with respect to the manufacturing plan. The whole history of each manufacturing operation is then linked to the product definition that is not currently the case in CAD-centred design approach.

The main recommendations for future work are:

- The application of the KBE software to more complicated academic and industrial case studies.
- The implementation of product-process relationships database that could further take into account more manufacturing physical and technological phenomenon that are already-known; for instance vibration, or dynamic behaviours during machining operations.

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Product Design Models for Global Product Development

Product Modelling for Configurable Design in Advanced CAD System

E. Ostrosi, A. Coulibaly, and M. Ferney

Abstract Design for configuration provides an efficient and effective means to realise the product variety. This chapter tackles the product modelling in advanced CAD systems for product configuration using an UML (Unified Modelling Language) approach and a computational model. The introduction of fuzziness to capture the subjective nature of the design for configuration permits to consider different use cases in the early conceptual design phase of the product. Furthermore, the building of multiple fuzzy models, which correspond to the multiple views of a configurable product, permits to propose both the functional architecture and physical architecture to configure a product. Then, the computational model permits to generate a solution which satisfies the customer requirement and the constraints of different process views. The association of the computational model and the CAD parametric model allows the generation of different configurations in a CAD system. An application shows the potential of the proposed approach.

Keywords Mass customization · Knowledge management · Product design

1 Introduction

Globalisation, market satisfaction and fragmentation, and rapid innovation are redefining the way that many companies design and manufacture. The dynamic customer needs demand a quick response from the companies. Companies that can provide customisation and increased product variety improve customer satisfaction and enjoy significant competitive advantage of those that cannot. Indeed customers are shifting their preferences from traditional products to customized products. Product customization process demand companies to concentrate their efforts on the individual requirements of the customers.

Design of configurable product family or design for configuration has emerged as an efficient tool to deal with the new challenges of a constantly dynamic and volatile market. Design for configuration provides an efficient and effective means to realise the product variety. Design for configuration is the process which generates a set of product configurations based on a configuration model and is characterized by a configuration task [1–5]. The configuration task then consists in finding the configuration of a product by defining the relations between its components in order to satisfy a set of specifications and a set of constraints imposed on the product [1, 4–6]. An essential characteristic of the conceptual design of a configurable product family is the product modelling [2, 5]. The effective modelling of a configurable product family must be capable to represent the complex relationship between the components of a product on the one hand, and the members of the family, on the other hand [7–8].

Modelling must deal with the problem of generation and derivation of the different products, and thus carry out the variety of the new and innovative products. Product modelling process must consider explicitly the issues involved in product realization process, such as manufacturing, assembly, maintainability ... etc. with their views to influencing simultaneously, the development of configurable products. At early design stages the product is usually freely conceptualized, the knowledge of the product is incomplete and the possibilities for lifecycle considerations are many [10]. Design for configuration must take early into account the different views of the product which occur during the process, the great number of product variants which are generated by the process and also the customer-oriented characteristic of the configurable products. The customization process must include the entire spectrum of product realization according to the product view framework [9]. Therefore, the configurable product design can be considered as the mapping process between the product specification

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view, the functional view, the physical view and the process view in order to meet certain customer needs characterized by a set of functional requirements.

Design for configuration process is also characterised by many degrees of freedom due to the individualized requirements of the customers and the nature of the engineering design. Indeed, engineering design can be considered as a process of reducing the uncertainty with each design alternatives is described. During the design process, the designer deals with some distinct forms of uncertainty such as imprecision, randomness, fuzziness, ambiguity and incompleteness [10–14].

The development of configurable products increases the complexity of the design process. Working with a large number of product variants proves to be difficult. The introduction of fuzziness to capture the subjective nature of the design for configuration process, using the UML for the building of multiple fuzzy models, which correspond to the multiple views of a configurable product, permit to structure the multi-views product architecture.

This chapter is structured in three sections. In the second section, the different models are proposed for architecture presentation of product configuration. An application illustrates the different models of the proposed modelling. In the third section, the computational model is presented. In the fourth section an application on a CAD system is presented. Finally, the results and the perspectives are presented in conclusions.

2 Fuzzy UML Based Models Building

2.1 Notations

The following notations are used for the indices:

- $\boldsymbol{I}_{\mathrm{R}} = \{1, 2, ..., n\}$ is the set of indices used for customer requirements; $i \in \boldsymbol{I}_{\mathrm{R}}$ is customer requirement number; n is the number of requirements.
- $\boldsymbol{J}_{\mathrm{F}} = \{1, 2, ..., m\}$ is the set of indices used for product functions; $\boldsymbol{j} \in \mathbf{J}_{\mathrm{F}}$ is function number; m is the number of functions.
- $\boldsymbol{K}_{\mathrm{S}} = \{1, 2, ..., q\}$ is the set of indices used for alternative solutions; $k \in \mathbf{K}_{\mathrm{S}}$ is solution number; q is the number of solutions; $\boldsymbol{K}_{\mathrm{S}} = \left\{\boldsymbol{K}_1, \boldsymbol{K}_2, \ldots \boldsymbol{K}_w \ldots \boldsymbol{K}_y\right\}$is a partition of the set $\boldsymbol{K}_{\mathrm{S}} = \{1, 2, ..., q\}$. A subset $\boldsymbol{K}_w$ represents the subset of indices corresponding to some alternative equivalent solutions; y is the number of parties in the partition.
- $\boldsymbol{H}_{\mathrm{C}_t} = \{1, 2, ..., g_t\}$is the set of indices used for constraints for the process view t, $t = 1, 2...v$; $h \in \boldsymbol{H}_{\mathrm{C}_t}$ is the constraint h in the process view t;g_t is the number of constraints for the view t; v is the number of process views.

2.2 Generating Functional Architecture

In most mechanical engineering applications, a combination of all three types of conversion: energy, material and signal, is usually involved. The conversion influences the function structure decisively [15]. Then the functional architecture of system can be represented by the automate (Fig. 1) which has three storage units (Input Unit, Output Unit, Control Unit) and one processor (Processor Unit). All are connected by four transmission lines.

The automate performs the following cycles: preparatory cycle and running cycles. Each cycle can be broken down into elementary steps:

Preparatory cycle:
Step 1: Receive energy into Input Unit (Source Unit);
Step 2: Load initial information into Control Unit;
Running cycle:
Step 1: Transmit the energy from Input Unit (Source Unit) to Processor Unit;
Step 2: Process the energy in Processor;
Step 3: Transmit the energy from Processor into Output Unit (Working Unit);
Step 4: Transmit the content of information from Output Unit (Working Unit), Input Unit (Source Unit) and Processor Unit into Control Unit.

The cycles of automate permit to generate a functional structure regarding the types of conversion: energy, material and signal. The primary and secondary flows [15] have been used to derive the functional architecture.

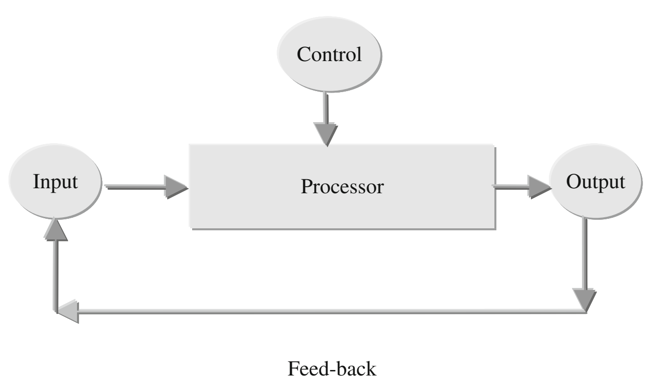

Fig. 1 Automate for generating functional architecture

2.3 The Fuzzy Product Specification and Function Model

The main concept behind fuzzy sets is most easily grasped if one has in mind that in every day life, and thus also in a lot of engineering applications for mathematics such as design for configuration, one does not directly meet with sets with crisp "borderline", but quite often it seems that there exists something like a gradual transition between membership and non-membership [13]. The design problem starts by specifying the universal set of customer requirements and the universal set of product functions. Specifications and requirements in the real design world are commonly fuzzy. The communication between the designer and the customer can not happen without such fuzziness, that both designer and customer allow for each other. The language between the designer and the customer always has fuzziness. Let us note $\boldsymbol{R} = \{r_i\}, i \in \boldsymbol{I}_{\mathrm{R}}, \boldsymbol{I}_{\mathrm{R}} = \{1, 2, ..., n\}$ the set of customer requirements, where r_i (e.g. *admissible manual force*) is the fuzzy set of requirement i. Then the membership function $\mu_{r_i}(x)$, where x (e.g. force) is an element in the fuzzy set requirement r_i (e.g. admissible manual force), represents the customer preference for the values of x (e.g. force).

For instance, in the case of a power system the user can consider different cases related to the loads in the working units (Fig. 2). Each use case corresponds to a state of system. Hence, a state is inherent for each unit of the system. Furthermore, each state can be characterised by data.

There is a relationship between customer requirements and the product functions. Once the customer requirements and the product functions have been determined, the designer is usually interested in determining how a customer requirement is related to a product function. A relationship between the requirements and functions would rather be given with intermediate degrees than "yes" and "no".

Let us note the universal set of customer requirements $\boldsymbol{R} = \{r_i\}, i \in \boldsymbol{I}_{\mathrm{R}}, \boldsymbol{I}_{\mathrm{R}} = \{1, 2, ..., n\}$, where r_i is the ith requirement and the universal set of product functions $\boldsymbol{F} = \{f_j\}$, $j \in \boldsymbol{J}_{\mathrm{F}}, \boldsymbol{J}_{\mathrm{F}} = \{1, 2, ..., m\}$ where f_i is jth function. A fuzzy relationship $\tilde{\Re}_1$, characterised by the membership function $\mu_{\tilde{\Re}_1}$, can be defined between the universal set of customer requirements $\boldsymbol{R} = \{r_i\}$ and the universal set of product functions $\boldsymbol{F} = \{f_j\}$. The membership function, denoted $\mu_{\tilde{\Re}_1}(r, f)$ and defined in [0,1], indicates in what degree a requirement can be accomplished by the set of functions. Or in what degree a function can be characterised by the set of customer requirements. The main functions $\boldsymbol{F} = \{f_j\}$ of power system are represented by the class diagram (Fig. 3). The fuzzy relationship $\tilde{\Re}_1$, between the universal set of customer requirements $\boldsymbol{R} = \{r_i\}$ and the universal set of functions $\boldsymbol{F} = \{f_j\}$, can be represented by a membership matrix $\boldsymbol{R} \times \boldsymbol{F}$.

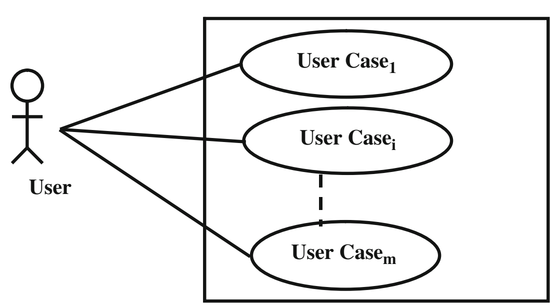

Fig. 2 Use case diagram

Functional structures are of great importance in the development of customer-oriented products. The functional structure of a product is the representation of functional elements of the product [16] and their interrelationships that involve decomposition and/or dependency. Functional modelling has been investigated in the case of single products as well as product families [9, 17–21]. Usually the functional structure of an individual product is indicated by a crisp representation. For example, in a graph representation the product functions are symbolised by nodes and their relationships are symbolised by edges. Each edge is characterised by a membership function, which takes the value of 1 if there is a relation between the two considered functions, and the value of 0 if there is no relation. The graph representation of the functional structure is called functional network or functional structure. In the case of a product family, a family function structure can be used, where the family function structure is the union of all variant function structures [15, 22–24]. Figure 4 represents the collaboration diagram representing functional architecture of a power system. It models functional and dynamic aspects of the system representing interactions between functions.

However, the relative lack of transparency of the relationships between input and output, the relative intricacy of the necessary physical process are some difficulties related to the setting up a functional network. For example, in the case of original design [14], neither the functions nor their relationships are generally known. Hence, an uncertain functional network can be obtained. Otherwise, in the case of the adaptive design [14], the general structure of the product, with its components, is much better known. Hence, a more precisely functional network can be obtained. However, in both cases, we are in the fuzzy domain. Given the universal set of functions $\boldsymbol{F} = \{f_j\}$ of a configurable product, the relationship between the elements of $\boldsymbol{F} = \{f_j\}$ can be characterised by different degrees of interaction. Hence, to describe these interactions inside the functional network, a fuzzy relationship $\tilde{\Re}_2$ can be defined. The fuzzy relationship $\tilde{\Re}_2$ is characterised by the membership function $\mu_{\tilde{\Re}_2}(f, f)$ which takes values between 0 and 1. A membership of 1

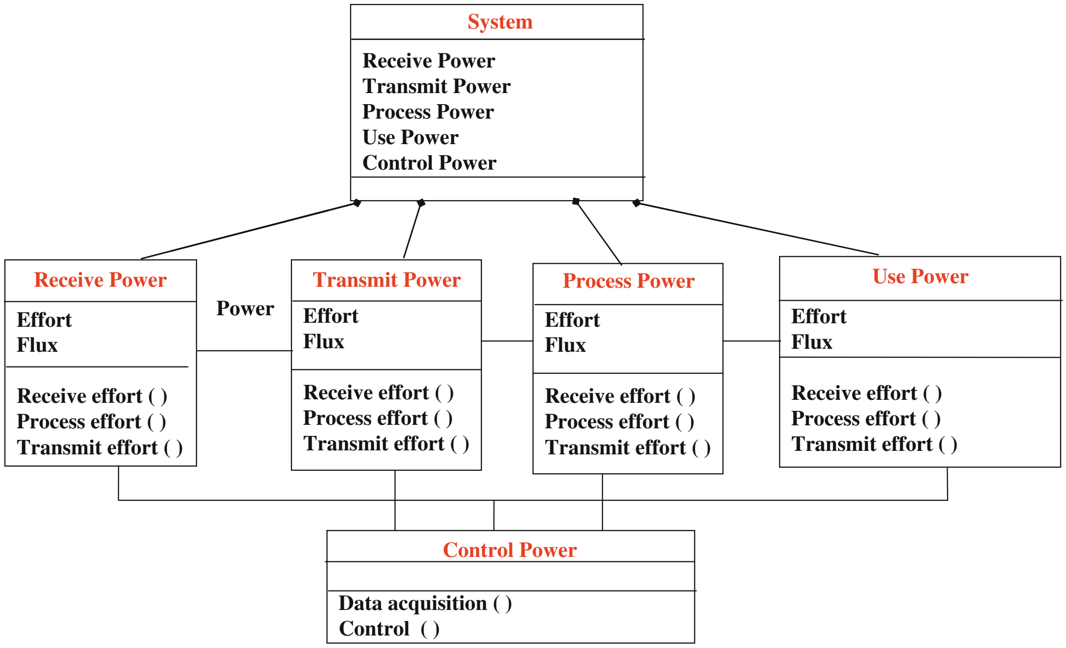

Fig. 3 Functions' class diagram of a power system

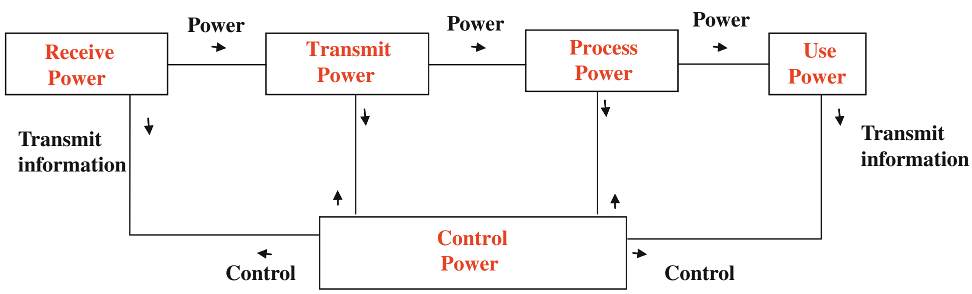

Fig. 4 Collaboration diagram representing functional architecture of a power system

represents that the designer has definitely identified a relationship between a couple of product functions, 0 that he or she has not. In practise, the logical relationships between product functions may be sometimes apparent and sometimes unclear. Hence, the designer could use an intermediate degree between 1 and 0. The functional network characterised by the fuzziness is called fuzzy functional network. The fuzzy functional network permits to facilitate the configuration product and to start the design with incomplete data. Indeed, the complete function structure can be obtained by iterations and it depends very much on the experience of designer.

2.4 The Fuzzy Physical Solutions Model

Each function in the set of product functions can be fulfilled by different alternative solutions. Different methods are used to represent the relationship between product functions and the solutions [19]. In design real life, a product function can be better fulfilled by a solution k than by a solution k'. Sometimes a solution may be apparent to a product function, but sometimes not. Some possible and uncertain solutions are not represented in that binary logic. Hence, we should use an intermediate degree between 0 and 1 as elements of the relationship between the product functions and alternative solutions. In this interpretation, an alternative solution can satisfy in a certain degree the universal set of functions. Or, a function in the set of product functions can be fulfilled with a certain degree by universal alternative solutions. This aspect implies that the relationship between the set of functions and the set of physical solutions is a fuzzy one.

Let us consider a power system representing by the class diagram (Figs. 5 and 6) and note the universal set of alternative solutions $\boldsymbol{S} = \{s_k\}, k \in \mathbf{K}_S, \boldsymbol{K}_S = \{1, 2, ..., q\}$ where s_k is the kth alternative solution. A fuzzy relationship $\tilde{\Re}_3$, characterised by the membership function $\mu_{\tilde{\Re}_3}$, can be defined between the universal set of product functions $\boldsymbol{F} = \{f_j\}$

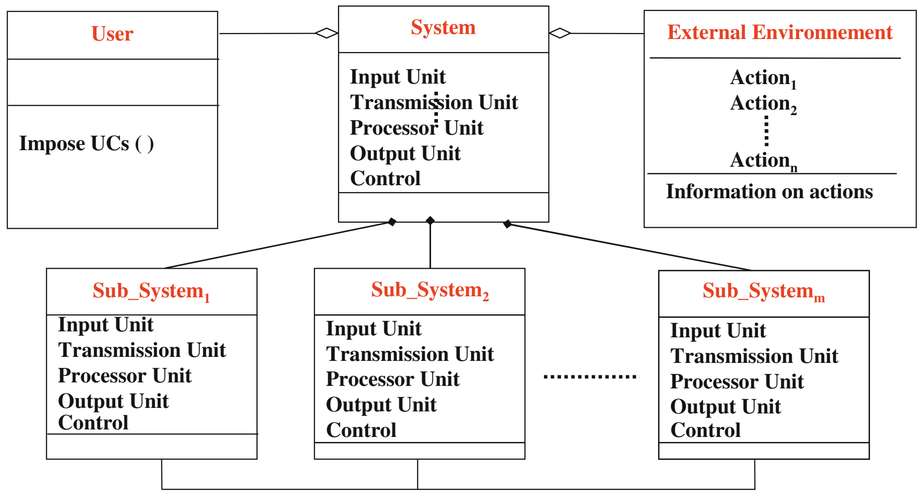

Fig. 5 Class diagram of a power system

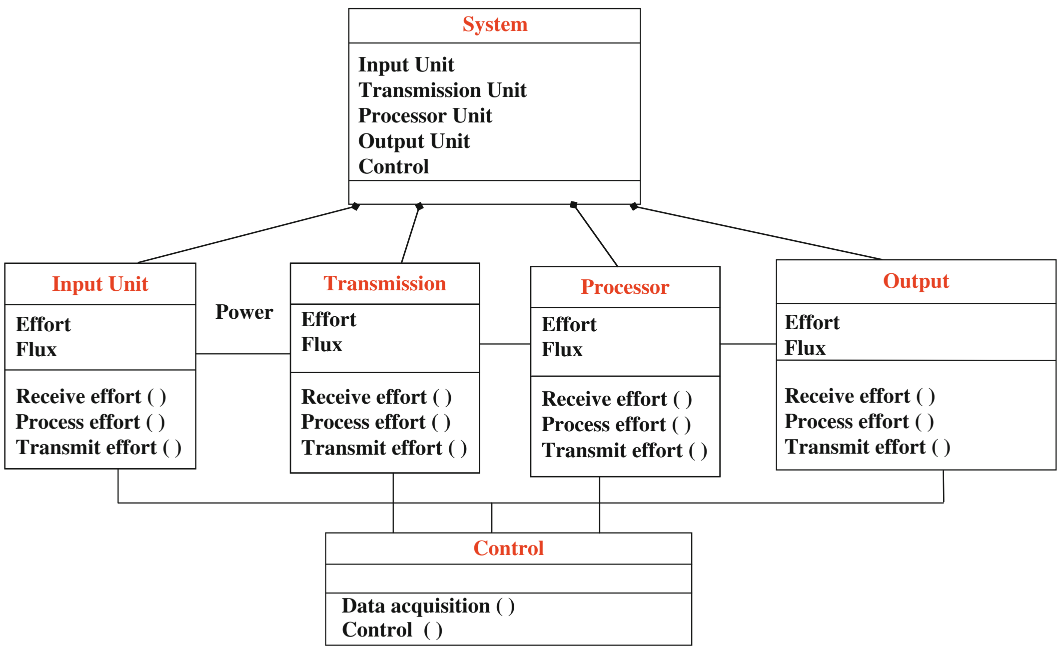

Fig. 6 Class diagram of a power sub-system

and the universal set of alternative solutions $S = \{s_k\}$. The membership function, noted $\mu_{\tilde{\Re}_3}(f, s)$ and defined in [0,1], indicates in what degree a function can be fulfilled by the set of alternative solutions. Or in what degree an alternative solution can satisfy the universal set of functions. Then the membership function $\tilde{\Re}_3$ can represent the designer perception for the characterisation of a product function by the set of alternative solutions. In this way, the fuzzy relationship between product functions and alternative solutions could represent better the continuous or approximate reasoning of the designer.

Let us consider a power transmission configuration. Each unit can perform one function or, a function can be performed by one or more units. Then a function–solution fuzzy relationship $F \times S$ can be build. Figure 7 represents physical architecture of a power system inferred from its functional architecture.

2.5 The Fuzzy Constraint Model

The integrated design is characterised by various activities involved in the design process. Each activity has its own view on the product and imposes its own constraints on the design model. For example, design for manufacturing and assembly is introduced earlier in the conceptualisation-synthesis stages

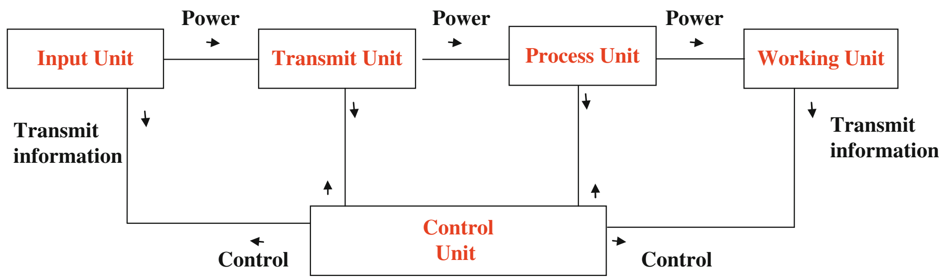

Fig. 7 Collaboration diagram representing physical architecture of a power system

of the design model [25]. It implies that finished design is optimum for both manufacturing processes required and the assembly techniques needed. Constraints in the real design world are commonly fuzzy. The communication between the designer and engineers, representing these views, cannot happen without such fuzziness. However, the constraints could have not the same degree of importance in the product design. For example, the assembly constraint *provide access for assembly* could be estimated as *very important* for a product design and as *relatively important* for another. Therefore, the fuzzy set *provide access for assembly* is defined for a range of products' design. Let us note $C_t = \{c_{ht}\}$, $h \in \boldsymbol{H}_{C_t}$, $\boldsymbol{H}_{C_t} = \{1, 2, ..., g_t\}$ the set of constraints for the process view t, where c_{ht} is the constraint h in the process view t. Then the membership function $\mu_{c_{ht}}$ represents the preference of the view t for the constraint c_h. For instance, for a product, the set of assembly constraints could be:

$$C_{\text{assembly}} = \{c_{11}, c_{21}, c_{31}, c_{41}\} \text{ with:}$$

$c1_1$: *Standardization*; c_{21}: *Proper spacing to ensure for a fastening tool*; c_{31}: *Maximize symmetry*, c_{41}: *Design mating features for easy insertion*.

There is a relationship between constraints and solutions. For example, the assembly constraint *apply locking elements which are easy to assembly* is an example of the fuzziness design. A solution can be a *locking element* which can respond to the constraint *easy to assembly* with a degree 0.7 and another solution with a degree of 0.9. Hence, the fuzzy relationship between *locking elements* and the constraint *easy to assembly* is defined. In this interpretation, values show in what degree the *locking elements* satisfies the constraint *easy to assembly*. Let us given the universal set of constraints $\boldsymbol{C}_t = \{c_{ht}\}$, $h \in \boldsymbol{H}_{C_t}, \boldsymbol{H}_{C_t} = \{1, 2, ..., g_t\}$ for the process view t, and the universal set of alternative solutions $\boldsymbol{S} = \{s_k\}$, $k \in \mathbf{K}_S, \boldsymbol{K}_S = \{1, 2, ..., q\}$ where s_k is the kth alternative solution. A fuzzy relationship $\tilde{\mathfrak{R}}_4$, characterised by the membership function $\mu_{\tilde{\mathfrak{R}}_4}(c,\ s)$, can be defined between the universal set of constraints $\mathbf{C}_t$ and the universal set of solutions $\boldsymbol{S} = \{s_k\}$. The membership function, noted $\mu_{\tilde{\mathfrak{R}}_4}(c,\ s)$ and defined in [0,1], indicates in what degree a solution satisfies the set of constraints. Then the membership function $\mu_{\tilde{\mathfrak{R}}_4}(c,\ s)$ can represent the designer perception for the satisfaction of the set of constraints by a solution.

3 Computing Model

3.1 Sets and Relationship Representation

In our computing model, the fuzzy sets are defined over the following sets, represented by vectors, as following:

- $\boldsymbol{R} = [r_i]$, $i \in \boldsymbol{I}_R, \boldsymbol{I}_R = \{1, 2, ..., n\}$, is the vector representing the set of customer requirements, where r_i is the $i$requirement; n is the number of requirements.
- $\boldsymbol{F} = \lfloor f_j \rfloor$, $j \in \boldsymbol{J}_F$, $\boldsymbol{J}_F = \{1, 2, ..., m\}$, is the vector representing the set of product functions, where f_i is jth function; m is the number of functions.
- $\boldsymbol{S} = [s_k]$, $k \in \boldsymbol{K}_S$, $\boldsymbol{K}_S = \{1, 2, ..., q\}$, is the vector representing the set of alternative solutions, where s_k is the kth alternative solution; q is the number of solutions.
- $\boldsymbol{C}_t = [c_{ht}]$, $h \in \boldsymbol{H}_{C_t}, \boldsymbol{H}_{C_t} = \{1, 2, ..., g_t\}$ is the vector representing the set of constraints for the process view t, where c_{ht} is the constraint h in the process view t; g_t is the number of constraints for the view t.

  In our computing model, the fuzzy relationships are represented by matrixes, as following:
- $\boldsymbol{A} = \lfloor a_{ij} \rfloor$, $(i, j) \in \boldsymbol{I}_R \times \boldsymbol{J}_F$, is the matrix representing the fuzzy relationship between the set of customer requirements $\boldsymbol{R}$ and the set of product functions $\boldsymbol{F}$.
- $\boldsymbol{B} = \lfloor b_{ij} \rfloor$, $(i, j) \in \boldsymbol{J}_F \times \boldsymbol{J}_F$, is the matrix representing the fuzzy relationship between the set of product functions $\boldsymbol{F}$. It represents the functional network.
- $\boldsymbol{D} = \lfloor d_{jk} \rfloor$, $(j, k) \in \boldsymbol{J}_F \times \boldsymbol{K}_S$, is the matrix representing the fuzzy relationship between the set of product functions $\boldsymbol{F}$ and the set of alternative solutions $\boldsymbol{S}$.
- $\boldsymbol{E}_t = [e_{hk}]$, $(h, k) \in \boldsymbol{H}_{C_t} \times \boldsymbol{K}_S$, is the matrix representing the fuzzy relationship between the set of constraints $\boldsymbol{C}_t$ for the process view t and the set of alternative solutions $\boldsymbol{S}$.
- $\boldsymbol{U} = \lfloor u_{ij} \rfloor$, $(i, j) \in \boldsymbol{K}_S \times \boldsymbol{K}_S$, is the matrix representing the fuzzy relationship between the set of product solutions $\boldsymbol{S}$. It represents the structural network.

3.2 Input Parameters: Customer Requirements and Process Constraints

During the design for configuration process, each product is customized according to the customer preference, which is an input parameter. Therefore, what requirements a particular *customer* has, and how the requirements are perceived by the designer, can be represented by the fuzzy vector $\boldsymbol{R}_{\text{customer}}$ over $\boldsymbol{R}$.

Furthermore, the restrictions that must be satisfied in order to produce a feasible solution are called the production constraints. These constraints, which are fuzzy in form, may derive from various considerations such as manufacturing, assembly, maintainability ... etc. They are input parameters, too. Therefore, what constraint a particular view t has, and how the constraints are perceived by the corresponding expert, can be represented by the fuzzy vector $\boldsymbol{C}_t^{\text{expert}}$ over $\boldsymbol{C_t}$.

3.3 Consensual Solution Generation

If a solution meets the fuzzy requirements of the customer and fuzzy production constraints, then it will be called a consensual solution. The fuzzy consensual set of product solutions satisfying the fuzzy set of product functions as well as the fuzzy set of constraints is computed from the equation:

$$\boldsymbol{S}_{\text{consensual}} = \boldsymbol{S}_{\text{customer}} \circ \boldsymbol{S}_{\text{constraint}} \tag{1}$$

where:

- $$\boldsymbol{S}_{\text{consensual}} = \{ (s_k, \mu(s_k)) \mid s_k \in \boldsymbol{S} \} \; k = 1, 2, \ldots, q \tag{2}$$
- $\boldsymbol{S}_{\text{customer}}$ over $\boldsymbol{S}$ is the fuzzy set of product solutions to mean possibilities of the solutions to satisfy the fuzzy set of customer requirements;
- $\boldsymbol{S}_{\text{constraint}}$ over $\boldsymbol{S}$ is the fuzzy set of product solutions to mean possibilities of the solutions to satisfy set of constraints for the set of process views;
- "∘" denotes an operation between two fuzzy sets. Two fuzzy sets of solutions are characterised by degrees of intersections. In our case, two fuzzy sets of solutions: $\boldsymbol{S}_{\text{customer}}$ and $\boldsymbol{S}_{\text{constraint}}$, both over $\boldsymbol{S}$ are searched. Then, the total consensus between $\boldsymbol{S}_{\text{customer}}$ and $\boldsymbol{S}_{\text{constraint}}$can be defined as the composition between $\boldsymbol{S}_{\text{customer}}$ and $\boldsymbol{S}_{\text{constraint}}$. The technique used in fuzzy theory is the **min** operation.

The fuzzy solutions $\boldsymbol{S}_{\text{customer}}$ over $\boldsymbol{S}$ is computed based on the fuzzy set of product functions, noted $\boldsymbol{F}_{\text{customer}}$, and the consensual fuzzy relationship between product functions and solutions, noted $\boldsymbol{D}'$. Indeed, the fuzzy relationship between product functions and solutions must be consensual in respect to the fuzzy functional network. Therefore, the relationship between the function and solution must be updated considering the influence of functional network on this relationship. It yields the consensual fuzzy relationship between function and solution. Thus, the fuzzy set of product solution $\boldsymbol{S}_{\text{customer}}$ over $\boldsymbol{S}$ is computed from:

$$\boldsymbol{S}_{\text{customer}} = \boldsymbol{F}_{\text{customer}} \circ \boldsymbol{D'} \tag{3}$$

where:

- The fuzzy set of product functions $\boldsymbol{F}_{\text{customer}}$ over $\boldsymbol{F}$ from costumer requirements $\boldsymbol{R}_{customer}$ is computed from the equation:

$$\boldsymbol{F}_{\text{customer}} = \boldsymbol{R}_{\text{customer}} \circ \boldsymbol{A} \tag{4}$$

- The fuzzy consensual fuzzy relationship between product functions and solutions is computed from the equation:

$$\boldsymbol{D'} = \boldsymbol{B} \circ \boldsymbol{D} \tag{5}$$

- "∘" denotes an operation between a fuzzy set and a fuzzy relationship (Eqs. (3) and (4)) or between two fuzzy relationships (Eq. (5)). The *max-min* composition is proposed to be used in the Eqs. (3), (4) and (5). From decision making point of view, *max-min* operation consists in considering as optimal, the strategy that corresponds to the greatest minimal conditional result, among minima conditional results of different strategy [12, 13].

On the other hand, the fuzzy solutions $\boldsymbol{S}_{\text{constraint}}$ over $\mathbf{S}$ is computed based on the fuzzy set of product solution $\boldsymbol{S}_t$ over $\boldsymbol{S}$ for t=1,2...v, where $\boldsymbol{S}_t$ mean possibilities of the solutions to satisfy the fuzzy set of constraints $\boldsymbol{C}_t^{\text{expert}}$over $\boldsymbol{C}_t$ of the view t. It is computed from the equation:

$$\boldsymbol{S}_{\text{constraint}} = \boldsymbol{S_1} \circ \boldsymbol{S_2} \circ \cdots \circ \boldsymbol{S}_t \circ \cdots \circ \boldsymbol{S}_{g_t} \tag{6}$$

where:

- $$\boldsymbol{S}_t = \boldsymbol{C}_t^{\text{expert}} \circ \boldsymbol{E}$$
- "∘" denotes an operation between some fuzzy sets, in the Eq. (6). The fuzzy sets of solutions $\boldsymbol{S}_t$ are characterised by degrees of intersections. Then, the total consensus can be defined as the composition between the fuzzy sets of solutions $\boldsymbol{S}_t$. Like the Eq. (1), the min operation is proposed to be used.

– "∘"denotes an operation between a fuzzy set and a fuzzy relationship, in the Eq. (7). In similar with the Eq. (4), the max-min operation can be used.

3.4 Optimal Configuration

A configuration can be described by a set of quantities, some of which are viewed as variables during the optimisation process. Those quantities being fixed during the configuration process are called preassigned parameters. The other quantities not preassigned are called design variables. The preassigned parameters, together with the design variables, will completely describe a configuration. It can happen that the experts are not free to choose certain parameters, or it may be known from experience that a particular value of the parameter produces good results. For instance, the number of modules in a configuration can be a preassigned parameter. Any set of values for the component members represents a configuration design. The modular configuration can be optimised automatically when component members are allowed to exits or not in a module. This suggests that a component member is limited to the values 1 (the component member exists in a module), or 0 (the component member is absent in the module). Then, the optimal product configuration problem can be formulated as follows:

Given the fuzzy structural network represented by matrix $\boldsymbol{U} = \left[u_{ij}\right]$ and the consensual fuzzy set of solutions from Eq. (2), find p-fuzzy subsets of solutions called module, such as the "distance" between each alternative solution and the nearest module be maximal satisfying following mathematical constraints:

1. *Alternative Consensual Solution Constraint.* The elements of the set $\boldsymbol{S}$ can be partitioned into classes $\boldsymbol{S}(\boldsymbol{K}_w) = \{s_k\}$, $k \in \boldsymbol{K}_W$. It ensures that one alternative solution in a class is assigned to exactly one module.
2. *Number of Modules Constraint.* It requires that exactly p modules are located. This constraint insures that the number of modules must be determined.
3. *Allocation Constraint.* It insures that all the other alternative solutions can be classified, if an alternative solution, considered as the best (nucleus consensual solution) is already classified.

4 CAD Application

4.1 Configuration Problem

A platform for bicycle configuration is demanded by a company. Indeed, the goal of the project is to respond quickly to the dynamic customer needs in a new global environmental and healthy context. Bicycle customization process demands the company to concentrate their efforts on the individual requirements of the customers. An essential characteristic of the configuration design of a configurable product family is the bicycle' CAD modelling. This modelling must deal with the problem of generation and derivation of the different bicycles, and thus it carry out the variety of the new and innovative products.

4.2 Configuration in Advanced CAD Systems

A prototype of a configuration platform is developed. The platform uses CATIA CAD modelling capabilities. In solving conceptual configuration design, there is a need to compute the solutions according to the model proposed in Sect. 3.

In advanced CAD system, the configuration design is strongly related to the parametric design. Indeed, the first task for product optimization in CAD system is the development of parametric CAD models (Figs. 8 and 9).

The second task is building the association between the parameters in CAD model and those generated by computing model. Figure 10 shows the result of configuration corresponding to a fuzzy set of requirement variation. It can be noted that the frame of new generated bicycle is different from the frame of the bicycle configuration represented in Fig. 9. Figure 11 shows some other bicycle configurations generated by the proposed platform related to the variation of the fuzzy set of requirement.

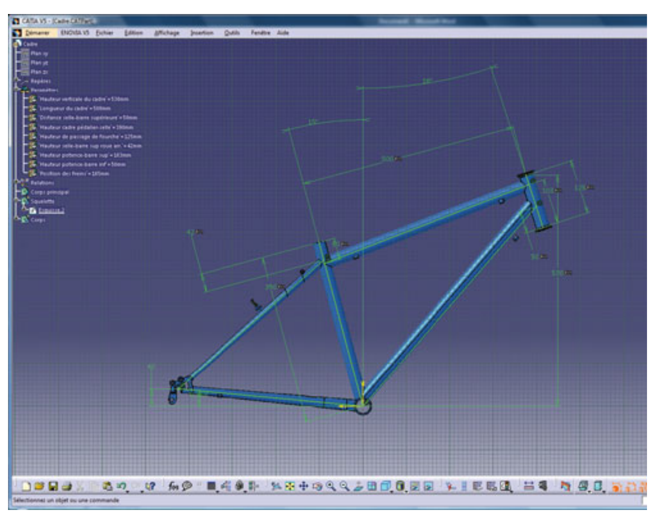

Fig. 8 Parametric modelling in CAD

Fig. 9 CAD model of a configured bicycle

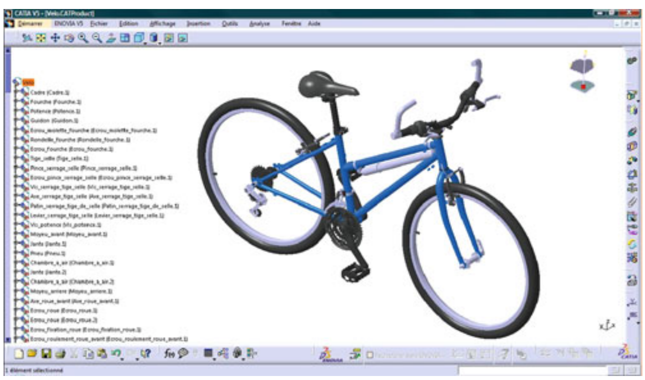

Fig. 10 New generated configuration

Fig. 11 Some generated configurations

4.3 Discussion

From the analysis of the proposed approach, we could identify some relative interesting contributions.

First, the configuration is not considered only an arrangement problem [1–8] but also a design problem.

Second, the application has shown that crucial aspect of product configuration in CAD system is the capability of the modeller to deal with the parametric design.

Third, the proposed approach allows the interaction between customer, designers and different actors. The configuration platform proposes to the designer the configuration which can satisfy the customer requirements.

Forth, the proposed approach allows the representation of the designer subjectivity. We may come up with some good questions: How do we determine a membership value? Roughly speaking, a membership value can be decided by whatever the designer feels or think, based on his knowledge and experience – that is the designer subjectivity. Thus, the values are dependent on designer. In the classic definition, the designer subjectivity was represented with 1s and 0s. Compared to this classic definition, it is more expressive, when any real number between 0 and 1 is used to define the designer subjectivity. With the membership values, the designer subjectivity can be represented completely. Thus the uncertainties are represented with the membership functions, as the designer feels or thinks. If the result, which must be validated finally by the designer, does not cover the behaviour of the given uncertainties, after the membership function is tuned, the designer restarts from the beginning.

Finally, an important aspect of the proposed approach is the problem of different mappings between different views. It is evident that the quality of results depends on these mappings. Thus it is important to analyse the quality of the convergence toward a configuration. For that, an alternative prototype platform is developed to compare the results generated by the proposed approach with what solution would really desire the customer. Thus this platform proposes directly to the customer some alternative solutions rather then the specification of requirements. Comparing the results would help to define better the operations on relationships and the definition of different membership functions.

5 Conclusions

In this research, a product modelling based design approach for product configuration is proposed. The configurable product design is considered as the mapping process between the product specification view, the functional view, the physical view and the process view in order to meet certain customer needs characterized by a set of functional requirements. The originality of this chapter is the introduction of fuzziness together with UML based modelling into multiple views product configuration and the association of the configuration computational results with a parametric CAD model. In this approach, the designer, using the fuzzy models, customise the product based on particular customer (user) requirements and the specific constraints of different process activities. Here, the configurable product design is considered as the mapping process between the fuzzy product specification view, the fuzzy functional view, the fuzzy physical view and the process view in order to meet certain customer needs characterized by a fuzzy set of functional requirements. The result of product modelling is, first, the product architecture both in functional and physical space and, second, the CAD model. Because of the uncertainty about the "true value" of a parameter or mappings, it is important to analyse how the solution derived from the model is sensitive to parameter values changing.

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Proposition of a Methodology for Developing a Database of Design Methods

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Abstract This chapter relates to the issue of the development of a database of design methods with emphasis on the methodology used to build it. The context of this research is the elaboration of a guide which helps designers in their choice of design methods. The chapter presents the long-term objective of this research and details the main challenges in the development of the database. It also discusses the methodologies used by previous authors and analyses the results of their implementation. The chapter concludes that the development of a new methodology is necessary in order to effectively develop a representative set of design methods.

Keywords Design methods · Database · Methodology

List of Abbreviations

BdF	Bloc diagramme Fonctionnel
BDF	Bloc Diagrammes de Fiabilité
FA	Functional Analysis
FAST	Function Analysis System Technique
FBD	Functional Block Diagram
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects, and Criticality Analysis
RBD	Randomized Block Designs
TRIZ	Teoriya Resheniya Izobretatelskikh Zadatch

1 Introduction

The complexity of the current product design process and the increase of project risks lead designers to use various design methods. These methods help to reduce new product development cycle, to minimize errors and to improve overall quality of products. This last decade has seen an explosion of the research in this field. It results in an increasing number of new methods for variable purposes. Thus, researchers have developed guides which aim to select appropriate design methods. Up to now, few guides exist to assist designers in this selection. These guides are supported by a database of design methods and tools. The focus of this chapter is the development of a database tailored for a specific application.

First, is presented the general context of this research, the assistance of the choice of design methods. Then, we focus on the problem of the development of the database. After experimentation of a methodology, a new one is proposed. Finally, the different contributions are detailed.

2 Assisting Designers in Their Choice of Methods

2.1 *Terminology Employed*

From an etymological point of view, "method" comes from the Ancient Greek term "methodos" formed with the prefix "meth" which could be translated by "afterwards" and with the suffix "odos" equivalent to "way, means" [1]. Its most common definition is: "Manner of carrying out, according to a reasoned step, an action, a work, an activity; technique". From this definition, we can observe some confusion between the terms "method" and "technique". Indeed, the author of this definition places these two words on the same plan, whereas others make distinctions.

In engineering design, many researchers proposed their own definition. According to Jones "methods are attempts to make public the hitherto private thinking of designers; to externalize the design process" [2]. In Cross' opinion, design methods are "any procedures, techniques, aids or 'tools' for designing" [3]. With these two examples, we can observe the broad variety of the definitions of design method. Because we want a large view of what design methods are,

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the definition of Cross is chosen in this chapter (includes any type of aids with design: tools, techniques, etc.). To go into detail on the use of the "method" term, the reader could refer to Araujo's work [4].

2.2 Engineering Design

According to Hales and Gooch [5], engineering design is "the process of converting an idea or market need into the detailed information from which a product or technical system can be produced".

One of the goals of this domain is to develop methods and tools more effective. It results a broad variety of different design methods. Indeed, from one particular method, it is possible to create a lot of variants. Figure 1 represents the genealogy of value analysis methods and their evolution [6]. It illustrates the quantity of variants which is possible to develop from a specific method.

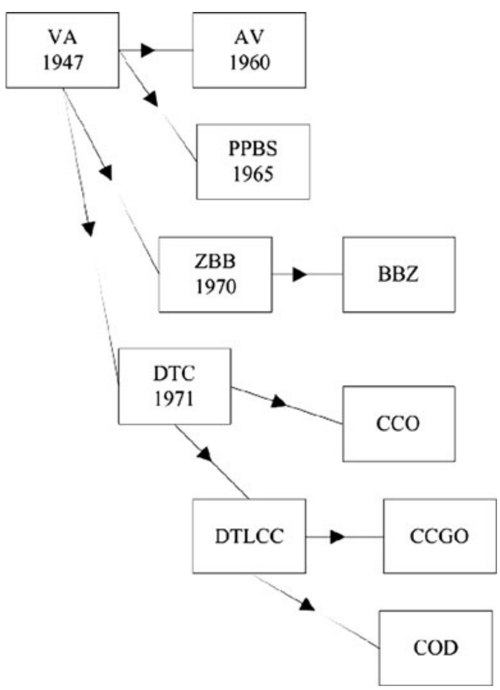


Fig. 1 Genealogy of value analysis methods [6]

2.3 Importance of the Selection

Design methods are inseparable from product development. First, they allow designers to structure and rationalize the design process. Therefore, the use of design methods is a conventional maturity indicator for innovative project. For instance, Herrera-Hernandez et al. [7] quoted "methodologies for supporting processes" as key factor to improve the product design process.

Moreover, design methods contribute to the whole strategy of the product design development. This is what Jones and Cross call "design strategy" [2, 3]. In particular, design methods improve the performance of the enterprise by optimizing costs, quality and time.

One of the objectives of engineering design is to develop new methods and to provide them to enterprises. Braun and Lindemann use the term "transfer" to illustrate the transition from academy to industry [8]. This transfer can be decomposed into three steps:

1. Selection : design methods are chosen depending on the need of the project
2. Adaptation : design methods are adapted to the specific project
3. Application : design methods are deployed

Several surveys reported the little use of methods in industries [9, 10]. For instance, Fig. 2 from [11] represents the results of a recent study which concerns the innovation management in enterprises. In [9], Geis et al. indicate that this bad transfer is the consequence of the lack of support in the selection of appropriate design method. Thus, the difficulty of the selection leads to methods being underused.

As a conclusion, the selection of design methods is a crucial task. Then, helping designers in their choice of appropriate design methods may lead to the success of the product development process.

2.4 Assisting the Choice of Design Methods

There is a need for a guide to know which method to use in a specific case. Few systems already exist in order to support the selection of design methods.

These guides are communicated through various ways: scientific books specialized in engineering design, articles in journals and conference proceedings, etc.

Historically, the first guides were based on the decomposition of the design process: for each phase, a set of design methods were recommended. Today, these guides still represent the majority of existing guides.

Another way for guiding the selection of design methods is to characterize methods with attributes. Method attributes could be defined as any information or property which enables to characterize a method. For instance, attributes could be the inputs/outputs of a specific method (see the input/output chart of Jones [2]). Attributes could also be the type of methods (creativity technique, multi-criteria decision making methods, etc.), the nature and the quantity of resources (time, human, material) and so on. For anextensive

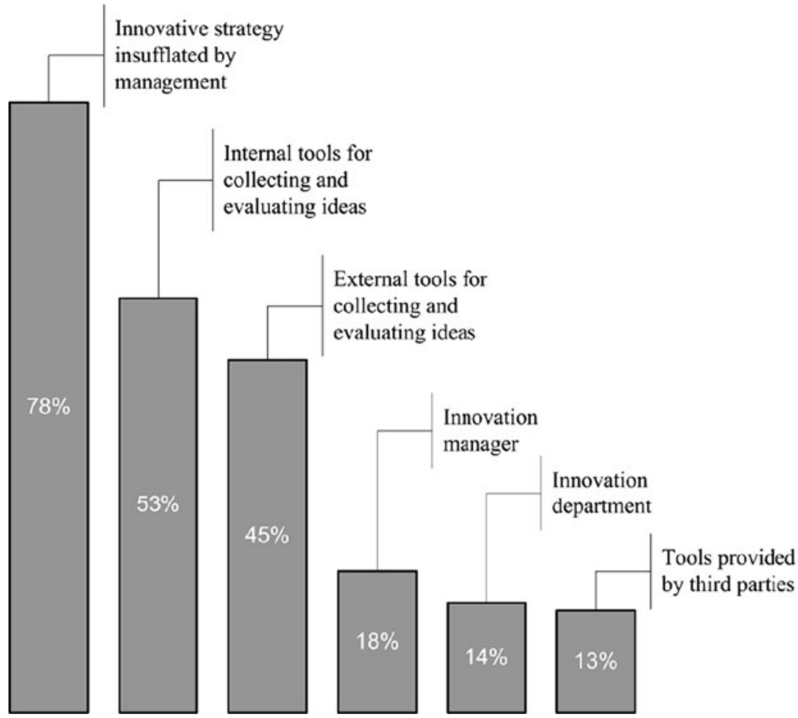


Fig. 2 Supports of innovation [11]

literature review of existing guides, the reader should refer to [12].

The existing guides vary a lot in their form, coverage of the process, etc. In spite of this variety, a specific database of methods has to be developed for each guide. In the next sections are detailed the methodology used by previous authors to create the database and the inherent problems.

3 Development of a Database of Design Methods

3.1 Risks Related to the Development of the Database

The database must be developed in relation to the specific application. It has to be valid for all types of designers, whatever their background is (product designers, ergonomists, engineers, etc.). It must be consistent with their practice. The guide will assist them in their specific choice of design methods or tools during the design process.

Thus, the developers of the guides must pay attention to the elaboration of the database. These data directly impact the validity of the final recommendations. If the data do not correspond to the practical work, users may not understand the recommendations or feel that they are irrelevant. In this case of misunderstanding, it may lead to the rejection of the guide.

3.2 Methodologies Previously Used

Among the existing guides, none corresponds to our application (different perimeter of the guide or obsolescence of the methods and tools quoted). A new database must then be developed.

Few authors provide details about their approach to elaborate the database. These authors use criteria and a rigorous methodology in order to make an objective selection.

Here, are presented two approaches, those of Jones [2] and Goodman-Deane [13] in order to develop the new methodology.

3.2.1 Jones's Criteria

In his input/output chart [2], Jones uses 35 techniques. These techniques have been selected from a literature review and the experience of the author. Five different criteria have been chosen:

- Effectiveness: Jones divides methods into traditional methods (such as design by drawing) and new methods (value analysis, for example). He chose to include only the new methods that are considered more effective than the old ones.
- Relevance: The techniques selected must be relevant with one of the three types of actions based on Jones' classification (divergence, transformation, convergence).

- Convenience: A technique judged to be relevant but not well covered in literature should be included.
- Familiarity: A technique is excluded if it is well covered by the literature and if Jones is not familiar with it.
- Criticism: A few well-known techniques criticized by some members of the scientific community are included in order to open the debate.

In spite of his attempt to make an objective selection, Jones warns the reader that this selection can't be independent of his own experience. This is the main bias of his approach.

3.2.2 Goodman-Deane's Approach

In her paper [13], Goodman-Deane details her approach to establish a representative set of 57 design methods. Unlike Jones, her study focuses on methods for involving and understanding users.

Her approach can be decomposed in four steps:

1. Identification: Several sources of bibliography are identified which collect series of design methods from the domains of product design and development, HCI, engineering design and ergonomics.
2. Inventory: 330 design methods are listed through the literature review.
3. Categorization: The identified methods are classified into three types: Analysis, Decision making, Ethnographic.
4. Selection: Among each type, a set of design methods is selected with focus on methods for involving and understanding users.
5. Validation: The selection is refined and validated with experts of the domain.

3.2.3 Synthesis

Among the criteria used by Jones, three out of five seem to be relevant to our study:

- Effectiveness: Each method or tool chosen must have proved its effectiveness on real case studies. This criterion is extended with the term "validity". This means that the method selected has a scientific background tested in practice.
- Relevance: This criterion is replaced by "representativeness". The methods selected must be representative of actions occurring in the design process (mechanisms: convergence/divergence; chronology: conceptual/detailed design). The methods have also to be representative of the background of the designer (product designers, ergonomists, engineers).
- Familiarity: This criterion is really a bias but is required in order to enter deeper into the conditions of use, limits and constraints of each method (next step of the research).

The Goodman-Deane's approach, rigorous and detailed, seems to be appropriated for our study. It separated the phase of collecting methods (divergence) from the selection strictly speaking (convergence). The representativeness of the set of methods is ensured by a classification which is a prerequisite of the choice. Before being evaluated, the selection is refined and validated with the experts of the field. In our study, these three points would be included in our approach (dissociation divergence/convergence; classification with criteria; involvement of experts).

4 Experimentation and Analysis

4.1 Experimentation

With respect to the previous synthesis, the chosen approach combines the five steps of Goodman-Deane with the criteria of Jones (integrated in the phases of classification and selection).

1. Identification: 14 sources of bibliography have been identified and summarized in Table 1. Different types of source have been processed: conference papers [14–16]; journal articles [17, 18]; thesis [19]; book chapter [20]; books [2, 3, 21–23]; website [24] or wiki [25]. No distinction with the terms of method, tool, and technique has been introduced. The identification was indifferent with sources specialized on one kind of method (for example, evaluation methods or creative techniques) with those which have general focus.
2. Inventory: The second step is the inventory of design methods quoted in the bibliography. A spreadsheet program was created.

The deployment of this methodology has been slow down because of the difficulties encountered in the identification process. These difficulties are analyzed in the next section.

4.2 Analysis of the Difficulties

Two types of problems were encountered during the application of the methodology. First, we were unable to determine if a method was already listed in the spreadsheet. Indeed, using the title of the method as single criteria for differentiate a method from another one turned out to be not sufficient. Thus, how to make sure that each method selected is unique?

Table 1 References identified and methods inventoried

No	References	Type of reference	Number of methods	Type of methods	Number of methods
1	[14]	Conf. paper	40	Design modeling methods	
2	[15]	Conf. paper	16	Evaluation methods	
3	[16]	Conf. paper	53	User methods	
4	[17]	Journ. article	16	User experienced research methods	
5	[18]	Journ. article	4	Methods to support Human Centred Design	
6	[19]	Thesis	60	Design methods	
7	[20]	Book Chapter	57	User involvement methods	539
8	[2]	Book	35	Techniques	
9	[3]	Book	8	Design methods	
10	[21]	Book	101	Creativity techniques	
11	[22]	Book	16	Tools	
12	[23]	Book	30	Design methods	
13	[24]	Website	21	Design methods	
14	[25]	Wiki	186	Creativity techniques	

Secondly, we noticed some hierarchical relationships between methods (the application of a specific method could be based on the use of a sequence of several other methods). If we don't take into account this characteristic, the list of design methods will be heterogeneous. Thus, how to make sure that the set of design methods has the same hierarchical level (the same level of abstraction)?

4.2.1 Uniqueness

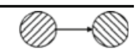
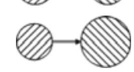
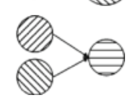
Each method in the database must be distinct from others. If this constraint is not observed, the recommendations of the guide could not be valid and relevant.

In practice, being sure that a method is different from another is far from being easy. First, a specific method could have several synonyms. For instance, Ishikawa diagram is also called fishbone diagram or cause-and-effect diagrams. Here, only one appellation must appear in the database (Ishikawa diagram or cause-and-effect diagrams, but not both). A particular method could also have several names due to the use of the original version term or its translation in other language. In France, people use equally the term "brainstorming" or its French translation "remue-méninges" for designate the same method. Thus, for the development of the database, a particular attention could be given when choosing the title which will appears in the guide.

Sometimes, the use of acronyms is also confusing. For instance, in French BdF is the acronym of "Bloc diagramme Fonctionnel" (Functional Block Diagram or FBD in English) and BDF is the acronym of Bloc Diagrammes de Fiabilité" (Randomized Block Designs or RBD in English).

Finally, using the title as single criteria for distinguishing one method from another is not sufficient. This analysis is quite similar with conclusions of Birkhofer [26] who defends the need of "tidy up design methods".

Table 2 Criteria for the distinction of design methods

Type	Function	Deployment	Scheme
Cohabitation	$=$	$\neq$	
Extension	$F_A < F_B$		
Combination	$F_A + F_B = F_C$		

In order to overcome this problem, Table 2 is proposed.

Here, in order to differentiate methods, we propose to characterize them in terms of aim/function and ways of deployment.

- If two methods have the same function but are applied in different ways, we retain both in the database. These methods *cohabit*. For instance, Brainwriting is a variant of Brainstorming. Both aim to generate ideas but the deployment is different. The association of ideas is realized verbally during a session of Brainstorming whereas it is realized on a sheet with Brainwritting. According to our criteria, Brainwriting and Brainstorming are two different methods: each would appear in the database.
- If two methods are strictly the same except for an addition of a function, we consider that they are distinct from each other. Here, a method is an *extension* of another. For instance FMECA is an extension of FMEA. Both would appear in the database.
- If a method has been created from several methods, the original methods and the new one are all specific methods. For instance, repertory grid is a composition of several interviewing techniques. All of them are retained in the database. There is a *combination* between several methods.

4.2.2 Homogeneity

From a methodological point of view, it is possible to distinguish various forms of interdependences between methods. First, it could be a temporal dependence: an evaluation tool such as weighted evaluation matrix follows to a creativity tool like brainstorming. Another form of dependency could also be a belonging relationship. This is this type of dependence which is developed here.

Design methods do not have the same level of granularity or abstraction. There are not homogeneous between them. Indeed, some of them are more practical whereas others are more conceptual. For instance, TRIZ is defined as a theory (TRIZ means "The theory of solving inventor's problems"). It could also be considered as a design method. TRIZ includes several analytical tools such as substance field analysis, contradiction analysis or required function analysis [27]. Thus, a belonging relationship could be observed between TRIZ and contradiction analysis. They have not the same level of granularity. The same kind of dependence could be observed between Functional Analysis (FA) and Function Analysis System Technique (FAST), a graphical mapping tool. Indeed, FA could be enhanced through the use of FAST.

In order to assist the selection of design methods, there is a need of a homogeneous set of design methods. As proved previously, existing design methods have not the same level of abstraction. Given that all levels could be important, the database would include both types of design methods.

This involves the development of a database keeping links between methods belonging to different levels of abstraction (design methods with high level of abstraction and others tools and techniques more practical and less conceptual than previous methods).

5 Proposition of a Methodology

5.1 Choice of Criteria

The difficulties encountered in the previous experimentation lead us to add two more selection criteria. Finally, in order to establish an appropriate database, six criteria have to be kept on mind in the selection of design methods. Some are inspired by the work of Jones, others result from the experimentation tested previously:

- Type: Here, the focus is on product design methods in a large sense (product is defined as material or non material goods). This excluded methods for project management (such as Gantt).
- (Scientific) Validity: Methods can be selected only if they have scientific background (theory).
- Uniqueness: Methods belonging to the database have to be distinct from each others.
- Homogeneity: Given that methods appearing in the database have not the same degree of abstraction, it is necessary to keep link between them.
- Representativeness: The methods and tools selected have to be representative of current practice in the industry. Indeed, the target users are in particular people who work or plan to work in industry.
- Familiarity: It is necessary to be able to characterize each method in detail (conditions of use, limits conditions, constraints, etc.). That's the reason why is introduced the criterion of familiarity as Jones did.

5.2 Methodology Proposed

The methodology proposed is inspired from the approach of Goodman-Deane. The six criteria developed above are included in this approach.

The methodology can be decomposed into seven steps. It combines phases of inventory and selection phases.

1. Identification: The methodology begins with the identification of relevant literature. All types of bibliography can be selected (conference paper, journal article, scientific book, etc.). The choice of these kinds of literature should provide a scientific validation of the selection. The literature identified has to focus on design methods but not on project management methods.
2. Inventory: The next step concerns the inventory of the methods and tools quoted in the literature selected. In this step, only the criterion of the type of methods enters into consideration (hypothesis that certain source of bibliography may mixes the two types of methods).
3. Selection 1: The first step of selection focuses on the uniqueness of the design methods and tools. In order to achieve this goal, it is possible to refer to Table 2. In this step, a second criterion is included, familiarity, with the help of experts of the field (interviews).
4. Classification 1: A first card sorting is realized based on the criteria of representativeness. All design specialities must be represented, same as all steps of the product design development.
5. Classification 2: A second card sorting with experts of the domain is realized on the criteria of homogeneity. An arborescence should be developed in order to distinguish the degree of abstraction, the macro and the micro level of methodologies (methods, tools, techniques, etc.).
6. Selection 2: The second and final selection is based on the previous criteria "homogeneity" and "representativeness".

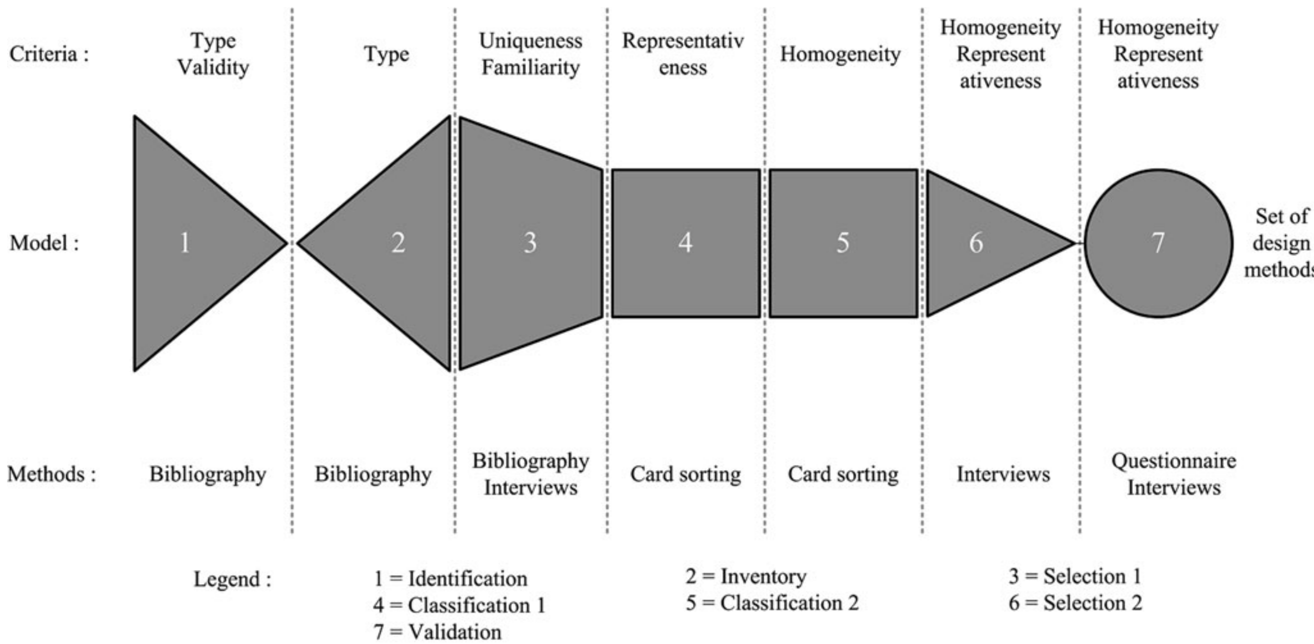


Fig. 3 Methodology for selecting a representative set of design methods

7. Validation: The validation should be realized with both academicians through interviews (specialists in the domain of design methodologies) and designers in industry through questionnaires.

The methodology proposed is illustrated Fig. 3.

6 Results and Discussion

Several contributions could be identified in this chapter.

First, from a technical point of view, a new database of design methods and tools will be developed. It will be tailored in order to design a guide which assists designers in their choice of methods and tools. This database will be real only after deployment of the whole methodology. Currently, steps 1, 2 and 3 have been realized. The next step will be the categorization of the methods with the help of criteria “representativeness” and “homogeneity”. This classification will be realized with expert of the field using card sorting technique.

Our main contribution comes from a methodological aspect. This chapter presents a generic methodology for developing a new database of design methods and tools. It should be workable for all applications. The user would only have to modify criteria in order to extend or narrow the perimeter. This methodology is particularly appropriated for application which requires rigour and justification.

Finally, the problem of the constitution of the database had been explored. Two criteria had been underlined: “uniqueness” and “homogeneity”. Thus, the ultimate contribution concerns the characterization of this problem.

7 Conclusion

The research reported in this chapter is about the development of a database of design methods and tools with particular focus on the methodology that has to be used. The long-term objective of the research, the development of a guide that helps designers in their choice of appropriate design methods, has been presented. Then, inherent problems with the development of the database have been analyzed. Finally, the experimentation of the methodology used by previous author led us to establish six selection criteria and to propose a new methodology.

The deployment of the methodology is at its early stage. The next stages of this approach will be developed in order to obtain a representative set of design methods. The database that will be created will be integrated in the future guide for selecting the right design method.

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Interdisciplinary Function-Oriented Design and Verification for the Development of Mechatronical Products

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Abstract Mechatronical products integrate components that are developed by different fields of engineering and combine them in order to provide new functionalities. The main challenge is the ever increasing complexity and the required degree of interdisciplinarity. The joint research project MIKADO adressed this demand by integrating domain specific development methods and tools into a more systems-engineering-oriented approach. Special emphasis has been placed on the early phases of product development in order to facilitate an early coordination between mechanical, electronical and software engineers and to provide them with easy means for the functional verification of virtual product models.

Keywords Mechatronics · Product development · Requirements engineering · Functional mock-up

List of Abbreviations

CAD Computer Aided Design
DMU Digital Mock-Up
FMU Functional Mock-Up
FOD Function Oriented Design
OEM Original Equipment Manufacturer
SME Small and Medium Enterprises
VDI Verein Deutscher Ingenieure

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1 Mechatronics – A Key Technology

Mechatronics is defined as a synergetic combination of mechanical, electronical and software engineering during the design and production of products as well as the layout of the required processes [1]. The increasing demand for cooperation between these disciplines is justified by the potential of overcoming consisting limits. Through their effective combination a product's performance and its functionality can be enhanced and new options for the design become available [2]. Hence, a broad range of product innovations is to be expected from this field.

But experience shows today that mechatronical product development is still a challenge for many companies since their development projects suffer from delays and quality problems. While product reliability is a crucial customer requirement, it is still a complex task to achieve reliability for mechatronical products [3]. Consequently, increasing the reliability of mechatronical products is the key factor for their broader acceptance.

2 Mechatronical Products Today and Current Challenges

Many functionalities of a mechatronical product rely on the combination of its heterogeneous subsystems. At the same time, this means an increase in complexity and requires a very well-coordinated interdisciplinary cooperation between the engineers from different fields of engineering during the product's development [2]. Both these challenges raise high demands on the development and production processes. Since costs increase with the amount of components that have to be integrated, the design and verification processes have to be reconsidered [4]. The result is a decrease in product reliability. This is partially due to the fact that approaches for defect prevention and the development of fault-tolerant products have not yet been applied to methods and tools for the development of mechatronical products. One of the

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resulting symptoms is a late and unexpected identification of design issues, either during the product development, after start of production or – in the worst case – after sales, in which case call backs of mechatronical products are very common. The second visible effect are frequent design changes and therefore design-steps, which are repeated unnecessarily often during the development phase.

Each of the different fields of engineering, which are involved in mechatronical product development, makes use of its own methods, formalisms and tools, respectively [5]. In doing so, the development of a mechatronical product usually is dominated by one knowledge domain. Often it starts with the design of its mechanical components. The engineers responsible for the design of the electronical and software components then have to arrange with the design constraints imposed by the mechanical structure of the mechatronical product. In worst case the design of the components happens asynchronously without proper communication between the fields of engineering. Both cases can be traced back to a lack of awareness of how design decisions can affect the components of other domains. Furthermore, there are no approaches for modeling the interdependencies between the components that could help raise such awareness.

The mentioned challenges become even more evident considering the increasing tendency of OEMs to require higher standards for defects liability from their subcontractors. Warranty costs due to an increase of failures in mechatronical products are being passed over to them and the original advantage of a better cost-benefit-ratio is compensated. Thus, the realization of failure-free products directly affects the suppliers and preserves their ability for innovation.

More and more companies rely on IT-tools during product development in order to manage the complexity of their mechatronical products. This often results in heterogeneous IT environments that have grown over time and consist of many isolated and poorly integrated applications. While those different applications may help improving specific subprocesses, their low level of integration creates technological and logistical barriers within the development processes as a whole. This makes an interdisciplinary cooperation even more difficult.

For a more efficient cooperation between the engineering disciplines but also between different companies within a supply-chain, a better integration of existing IT-tools is required. Unfortunately, the typical IT-tools in product development are not flexible enough and their integration requires a lot of customization. In many cases companies even adapt their processes to the IT-tools because it is more cost-efficient to do so. This is especially common for small and medium-sized enterprises (SMEs) [6].

Standardized methodologies, software interfaces and middleware solutions can help integrating the processes and IT-tools in product development projects. Therefore cost of process and software customization can be lowered which makes it easier for SMEs to cooperate with other companies within a supply-chain.

The VDI (Association of German Engineers) guideline 2206 [7] suggests a methodology for the development of mechatronical systems. It comprises methodical approaches for their design – especially in the early phases of product development. Appropriate software interfaces and middleware are missing. There are standards for the exchange of product models but no approaches for integrating all important IT-tools used during product development. A software platform for interdisciplinary and cross-company cooperation is required.

Already in the requirements definition phase these problems, as well as the complexity of mechatronical systems have to be considered since the interdependencies between the different engineering fields are an important factor [8]. The increasing amount of requirements that arises from the cooperation between the disciplines also makes it harder to overview their entirety [9]. This is especially true if requirements are documented in text documents, as still practiced in many companies. Drawbacks include the lack of sorting and filtering functions, complicated search mechanisms and thus the increased risk to overlook important requirements. New approaches for managing requirements that make it easier to overlook and verify their degree of realization during a product development process are needed.

The common approach in mechanical engineering of creating separate target and requirements specification documents [10] differs from how software engineers usually proceed during the requirements engineering phase. Those approaches as suggested by Rupp et al. [11] on the other hand cannot fully be applied to mechanical or electronical product components. Thus, approaches from the different fields of engineering have to be combined and adapted.

Besides the methodical approaches there are several software applications to support requirements engineering and management, slowly replacing the traditional document-based approaches. However, none of the applications supports the modeling of parametric links between requirements, functions and product components.

But especially for the development of mechatronical products companies need requirements management systems that support this holistic view on all the before mentioned aspects of a product. The system behavior that results from the interaction between the different components has to be modeled and requirements for this behavior have to be specified.

Besides the management of requirements, there is also a strong demand for strategies and tools that allow an early verification of the defined requirements. Today the state-of-the-art in requirements verification includes physical prototypes and the use of digital mock-ups (DMU). DMUs are virtual dummies for physical product components that help understanding the real components look-and-feel. Using DMUs can result in reducing the amount of iterations and changes during a products construction and minimizing the need for time-consuming and costly experiments with real physical prototypes. Currently DMUs are mainly used for the analysis of the designed space in vehicles, kinematic and assembly tests [12].

An advanced approach to DMU is the FMU (Functional Mock-Up). In addition to a DMU a FMU also partially reproduces a product component's functionality. Through the integration of simulation models and respective software applications it is possible to simulate behavior and usage properties in a realistic way. This allows for a comparison between behavioral requirements and a product's development status [12]. Furthermore, the impact of design decisions in the early stages of product development can be evaluated more accurately and the predictability of the system performance can be improved [13].

The application of FMUs is still in the initial stage and only parts of products can be verified. Instead of a seamless integration into product development processes as needed for the preparation of the simulation models, they are only loosely integrated. Accordingly, neither the access to product data from all the different fields of engineering nor the automated interpretation of simulation data regarding functional requirement satisfaction is possible yet [13, 14].

3 The MIKADO Cooperation Platform for Mechatronical Product Development

In order to meet the described requirements and to reduce the mentioned deficits, strategies, methods and tools were developed within the joint project MIKADO (mechatronical cooperation platform for requirements-driven verification and diagnosis). The consortium consisted of eight main partners, composed of OEMs, system vendors and research institutes. The project duration was 30 months.

The main objective of the project was to improve the existing approaches to mechatronical product development in order to enable an interdisciplinary concept of systems engineering. The aim was to establish a coherent and integrated basis for the development of mechanical, electronical and software components. For this purpose cross-domain and cross-company information and cooperation models have been developed. This also facilitated a more thorough cross-check between the virtual and the real system at any given point in time, which again yields a significant increase in the predictability of the system behavior. The improved quality in the development process goes hand in hand with enhanced product maturity, and in consequence improved system quality and reliability [15].

The research work was roughly organized in the following three areas:

- the integration of all data and tools through the MIKADO cooperation platform,
- the design, evaluation, analysis, automation and improvement of the interdisciplinary development processes, and
- the management of requirements and product functions as well as the software tools for their verification.

The integration platform – called the MIKADO cooperation platform – is the core of this approach. It integrates different software applications for the modeling of requirements, shared information and processes.

The aim of the MIKADO cooperation platform is to synchronize the domain specific development processes by allowing the access and sharing of relevant data interdisciplinary and providing a single point of access for all relevant software applications. It assumes that a structured exchange of work results and a transparent approach for providing engineering services from one field of engineering to another are the key factors for a successful interdisciplinary cooperation.

Consequently, the platform offers functionalities to access data which is stored in remote systems through an easy-to-use interface and to access software services provided by remote systems through a standardized application programming interface [2]. The software tools for the management of requirements and functions and for the verification, which will be examined closer in this chapter, are connected using these functionalities.

Aim of the process related research work was to create methodologies for the development of new and the improvement of existing product development processes. Both methodologies are supported by software applications and a set of best practice processes for the design phase of mechatronical products. The software applications allow for modeling processes, editing them, simulating them, comparing process variants, deploying them on a workflow engine, evaluating their real-life performance and comparing to-be process model with as-is process data. One special focus of these tools is the aspect of interdepartmental and cross-company cooperation as organizations often face the challenge of aligning processes from different departments or even independent companies. The different organizational units usually don't know any details about the other's processes, either because they simply don't need to or because they are not supposed to. Current cooperative process modeling tools do not support hiding process models from other cooperating users while still providing interfaces for aligning processes with them. In the MIKADO approach process models of different organizational units (departments or companies) can be combined as black boxes with interfaces without having externals see their exact behavior. This enables all partners to analyze the behavior of their processes (using simulation techniques) in interaction with other processes without disclosing confidential information. Cooperating companies in a supply-chain can adjust their processes more easily this way. The software applications for the management of requirements and functions and for their verification can be integrated in the workflow instances of the modeled processes.

For the functional verification of mechatronical product models following aspects have been developed in the MIKADO project:

- a methodical and tool-supported approach to requirements management,
- software applications for functional verification, and
- a methodical approach that combines the requirements management approach with the tools for functional verification.

The software application FOD (Function Oriented Design) [16] allows for managing requirements as well as provision of information needed for a functional mock-up. To exemplarily realize this functional verification a software prototype based on CATIA V5 and Ascet (Advanced Simulation and Control Engineering Tool) has been developed during project runtime. Furthermore, the FOD modeler and the software prototype have been integrated using the MIKADO cooperation platform (see Chap. 5).

4 Use Cases for the Development of Mechatronical Products

The requirements for the developed methods and software applications were derived from and verified with the help of several scenarios from real-world industrial development projects. They include examples from the industrial sectors machine tool building, power industry, facility management and automotive engineering (see Fig. 1). In this chapter the use case "car seat design and verification" will be discussed more closely.

During the development process of an automobile the aspect of safety has taken a major role. Legal regulations and growing customer expectations force car manufacturers to put special emphasis on it. In this context, the car seat is one of the most important systems as it provides key functions for the driver as well as the passenger. It is a dynamic subsystem in the overall passive safety system and has to fulfill diverse kinds of requirements, like protecting the person seated on it during a crash, being comfortable or making sure that traffic and traffic signs are visible to the driver.

Fig. 1 Use cases in MIKADO

Thus, verifying whether a car seat fulfills its requirements is a complex task. Its movement depends on the interplay of mechanical and electronical components. The comfort of the seat on the other hand is an aspect that can hardly be verified with a virtual prototype. That's why different types of verification approaches are required during the development of a car seat. Additionally, new simulation approaches have to be considered in order to simulate the mechanical and electronical components' behavior simultaneously and to make their dynamic interaction understandable.

The challenge becomes even more apparent as more components such as airbags or additional sensors get integrated in car seats. Every part adds to the overall complexity of the seats' dynamic behavior. On top of that, customization plays an ever growing role in the automotive sector. Customers require different designs and functionalities of a car seat and the car manufacturers try to respond to it.

5 Approach for Requirements-Driven Functional Verification

In the joint research project MIKADO a prototypical approach for a hybrid – mechanical and electronical – FMU has been developed. It has further been integrated in a

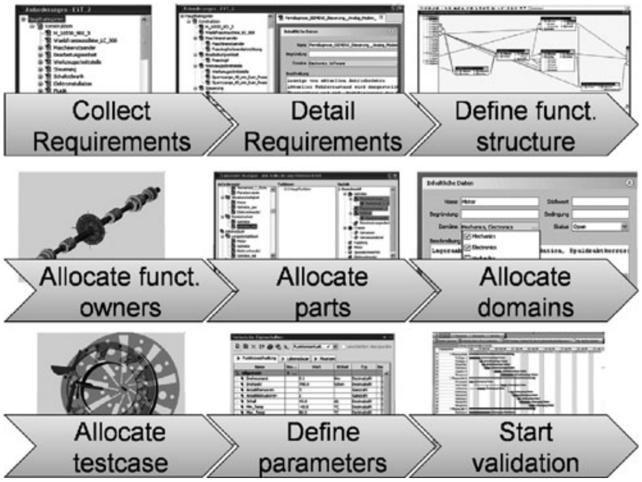

Fig. 2 Preparation procedure for requirements-driven functional verification

comprehensive approach for continuously tracking requirements and function fulfillment during a development project for a mechatronical product.

The realization of a requirements-driven functional verification requires some preparative steps, before the actual test can be carried out (see Fig. 2).

In order to support those steps, the FOD modeler, which is based on the phases of engineering design as defined by VDI (Association of German Engineers) guideline 2222, has been enhanced. In comparison to the document-based management of requirements and product functions FOD follows a model-based approach.

Requirements can now be collected, modeled, mapped to engineering disciplines and successively be interlinked. Doing so results in a requirements-net which is the basis for the coordination between the engineering disciplines.

After modeling the requirements, a parametric model of the product functions can be designed, detailed and connected with solutions and CAD models of the product parts. In the following refinement of requirements and function nets as well as component structures domain specific design methods, tools and models are increasingly applied.

Furthermore, it is possible to create an overall and calculable context, since the links between the different partial models can be detailed on a parametric level. Based on this, it is much easier to get an impression of how changes in one particular requirement, function or part can affect related elements. This is especially important for an interdisciplinary cooperation in product development.

For the modeling of and the interaction with the requirements, functions and components, FOD provides different editors (see Fig. 3), which will briefly be discussed in the following paragraphs.

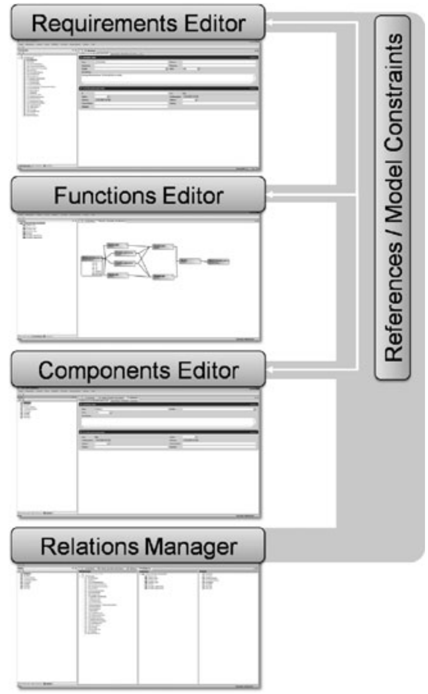

Fig. 3 Architecture of the FOD-modeler

The Requirements Editor consists of several sub-forms for the structured documentation of requirements. Each requirement can be assigned to specific categories which can be customized by the user. Documents which contain further information about the requirements can be linked and criteria (e.g. dimensions of a product component) can be defined as global parameters in the FOD model.

The functions that are defined during the concept phase as well as their relations can be modeled and visualized in the Functions Editor. Each function can consist of subfunctions and is assigned a set of in- and output parameters. Output parameters can be mapped to input parameters of other functions in order to create a net of connected functions.

Product parts and assemblies can be modeled and structured in a hierarchical tree-structure in the Components Editor. Each part can be assigned parameters and linked to corresponding CAD models.

Each partial model – the requirement, the function and component model – is a self-contained model which can thus be modeled independently. Links between them can be created at any time and can either be references or so called model constraints. References indicate that there is a relation between two elements. Model constraints by contrary represent semantics in a logical or numerical way and can be edited in the Relations Manager.

Those model constraints between requirements, functions and parts have a great value in practice, as they are an indirect connection between customer request and the mechanical system. Changes in requirements can cause direct changes in CAD models.

In MIKADO, this approach was refined by the possibility of domain allocation, in order to make an interdisciplinary requirements management possible and to transfer mentioned functionalities to support a mechatronical product development. Connections between requirements from different domains can be defined and thus the impact of changes in areas of other disciplines can be visualized.

The implementation of several views on requirements, functions, assemblies and constraints further improves the reduction of complexity even in large development projects. Those filter options include views for the management in which requirements can be visualized by dates or degree of compliance and allow for a direct assessment of projects' progress.

The complete FOD model can be considered as the common interface all engineering disciplines have to cater to and that interconnects them. Their usually differing and independent views on the mechatronic product are united and, in addition, the degree of maturity can continuously be checked.

Functional verification has several dimensions, which differ in complexity as well as in their degree of automatibility (see Fig. 4). In the MIKADO project they have in common that they are started from and administrated in the FOD modeler. For this purpose, the results are downloaded from the platform and saved with the tested requirements, after the tests are finished. An integrated documentation of the development process is thereby guaranteed.

In order to be able to provide products with a high standard of quality, an increased use of FMU tests is needed. In the MIKADO context, a FMU is defined as a set of tasks to verify a specific function of a product and gather

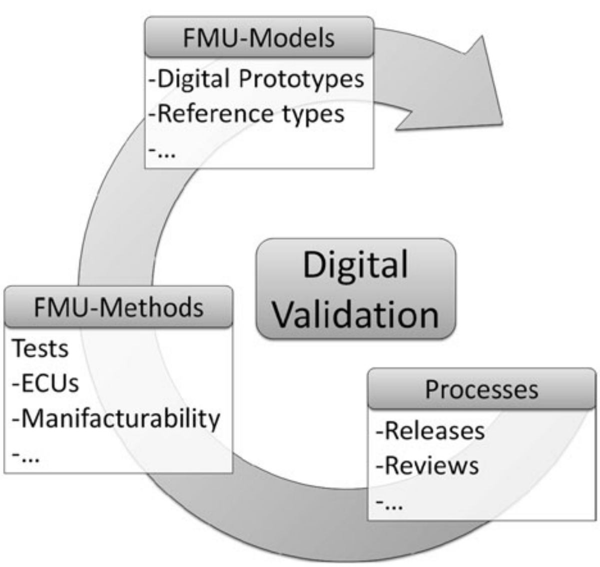

Fig. 4 Different approaches for digital verification

the therefore required information. Depending on what kind of functionality is to be tested, different software applications have to be taken into consideration. This might be a DMU-Viewer that allows for a static analysis to be carried out or a calculation tool for the simulation of a mechanical part's movements or their deformation. In comparison to other highly integrated approaches to system design the open architecture of the MIKADO cooperation platform allows for the easy use and coupling of different vendors' applications in order to define a FMU. In FOD any kind of FMU can be linked to parameters of a requirement and thus verify whether said requirement is fulfilled. The FMU itself is realized using regression tests, which are especially suitable if frequent changes occur in the product development.

For an effective application and documentation of single test runs it is necessary to create a reproducible and traceable procedure. Furthermore it is essential to be able to upgrade those tests in order to keep them in compliance with the requirements, which depend on the use case. To achieve this, the tests are organized in three parts:

- test templates,
- test objects, and
- test instances.

The FMU test software provides test templates which are stored in the MIKADO cooperation platform. Those are used by the FOD requirements management module to define the possible tests and to subsequently save the concrete test objects in the cooperation platform. Instead of precise values, test objects contain references to parameter objects. FOD can request the MIKADO cooperation platform to start a test. The current values are identified and saved in the test instance. The actual test either takes place in the requirements management software or any other software which is connected to the cooperation platform. To exemplarily show the possible functionalities of tests, several examples were implemented in CATIA V5 with an additional integration of mechatronical components. For this purpose geometrical checks were realized and methodologies were developed in order to test electronic control unit software, which is programmed with Ascet (Advanced Simulation and Control Engineering Tool), in interplay with virtual geometry.

Since all test elements are version-controlled it is assured that all tests are reproducible and traceable as well as they do reflect the current state of work.

6 Example of Use

One of the main problems in product development is the coordination of the involved domains. In the following paragraphs the advantages of the described MIKADO tools are

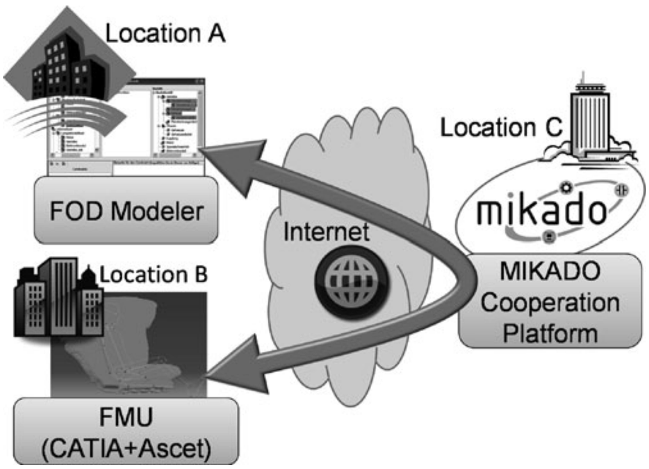

Fig. 5 Architecture of the MIKADO solution

demonstrated with the help of a use case from automotive engineering, more precisely the development of a car seat. While the whole system of a car seat has been focused upon during the project only one function, the adjustment of the car seat position, is presented in this chapter. Furthermore, other FMUs like a control system of a sunroof were implemented to further validate developed methods and tools, but are not described in detail in this chapter either. Figure 5 shows the architecture of the used MIKADO solution and points out the possibility of distributed working in different locations.

Within this use case the use of the improved FOD modeler helps to collect, document and manage all requirements for the seat in a central and comprehensive application. By linking the requirements on a parametric level, collateral development processes become integrated and thus interventions in other development domains become visible. As a direct result the amount of iterations needed during concept development can be reduced and changes in requirements can be realized with fewer costs as well.

Furthermore, in this context, the integration of FMU-processes is a large advantage. They are started directly in the FOD modeler to promptly and continuously test the impact of changes.

In this use case geometric tests have been implemented to automatically analyze the field of view and clash behavior in interaction with the automobile structure (see Fig. 6).

In order to do so, the test template is loaded in the FOD modeler, necessary parameters are chosen and uploaded to the cooperation platform. This data is automatically passed to the external application, which executes the test, and the test is started.

In case of the analysis of visibility those parameters are describing the position of the traffic light in comparison to the drivers' seat. Under consideration of the kinematics all possible positions of the seats are tested in CATIA V5 and all view rays are combined to a volume. If this volume completely cuts the schematic windshield of the car, the traffic light visibility is guaranteed (see Fig. 6a).

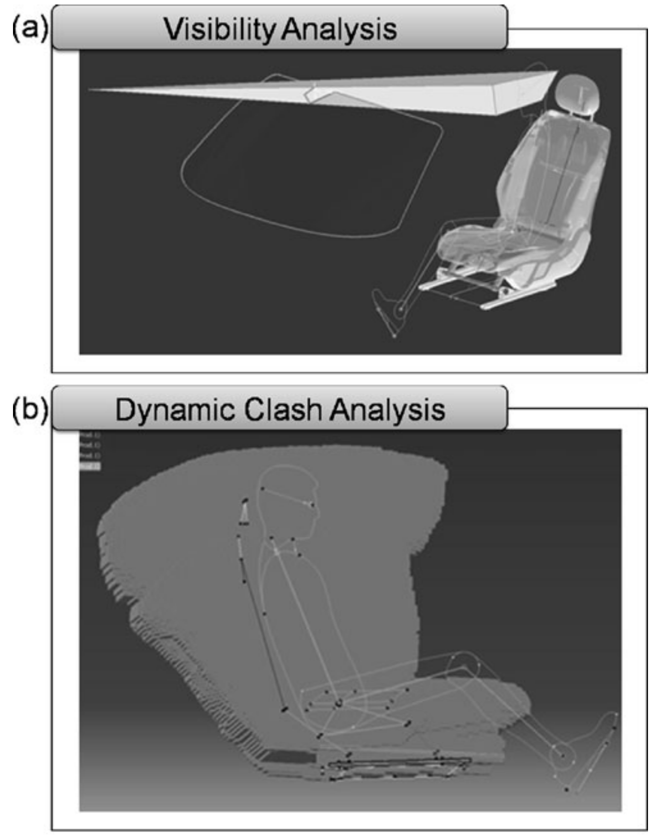

Fig. 6 Visualization of the test results

The clash analysis is similar to this procedure, but instead of view rays determining the field of view, the seat itself and its possible positions is used to create the volume (see Fig. 6b). If this volume cuts any of the surrounding structure, closer examinations have to follow and, in case, changes have to be carried out.

After the completion of the test, the results are uploaded to the MIKADO cooperation platform. They can be interpreted and allocated to the tested requirement in the FOD modeler.

7 Results and Future Work

In addition to methodologies and tools, the results of the joint research project MIKADO comprise examples of use, process solutions as well as consulting and implementation services (see Fig. 7).

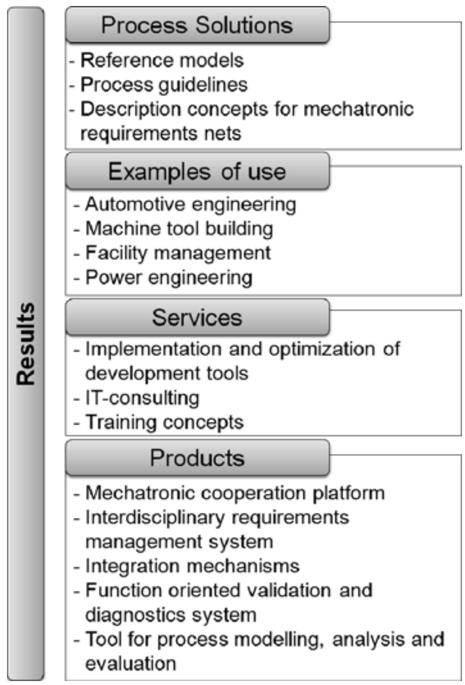

Fig. 7 Results of the joint research project MIKADO

The MIKADO cooperation platform will improve and accelerate the planning and execution of mechatronical product development projects. Interfaces for connecting commercial engineering tools to the cooperation platform guarantee the industrial applicability of the MIKADO solution in connection with existing system landscapes. This reduces investment costs and makes the MIKADO solution attractive, especially to SMEs.

The enhancements of the FOD modeler help to collect and manage all requirements of a mechatronical product as well as to define and depict their connections. Their continuous connection to functions, parts and CAD models allows for cross-checking the fulfillment of several geometric requirements.

Specific tests for functional and geometric analysis complete the Functional mock-up. They are started from and their results are managed directly in the FOD modeler as well as on the cooperation platform and thus make a continuous review of the products' degree of maturity possible.

The methodology for combining a comprehensive requirements management with a functional mock-up for the verification of requirements will be the basis for further research.

In addition, the results of MIKADO are planned to be used for commercial products, which will be sold by the project partners.

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Towards Semantic Virtual Prototypes for the Automatic Model Combination

R. Radkowski

Abstract This chapter presents an approach for the automatic combination of different models in order to build-up a virtual prototype automatically. Semantic Web techniques are used for that purpose; aim of the work has been to verify if Semantic Web techniques are suitable for that purpose. Therefore, the models that need to be combined become semantically annotated. The items of 3D models and multi-body systems are presented, which need to be annotated in order to facilitate an automatic combination of these two types of models. To combine them the relations between both models need to be identified. A reasoning mechanism is presented that indentifies these relations. The automatic combination of models simplifies the build-up of virtual prototypes. In future, it facilitates complex virtual prototypes that consist of multiple models. Due to the addition of a semantic to the models, the virtual prototype is denoted as Semantic Virtual Prototype.

Keywords Virtual prototype · Mechatronic systems · Semantic web techniques · Automatic model combination

1 Introduction

A virtual prototype (VP) is the computer internal representation of a real prototype [1]. Figure 1 shows the concept of the term VP to improve the understanding. The VP is based on the digital Mock-up (DMU). The DMU represents the shape and the structure of the product. Two models are the origin of the DMU: 3D-CAD models and the logical structure of the product. The VP extends the DMU, because further aspects are taken into consider, aspects like the kinematic, dynamic, strength or information processing. A computer-internal model represents each of these aspects.

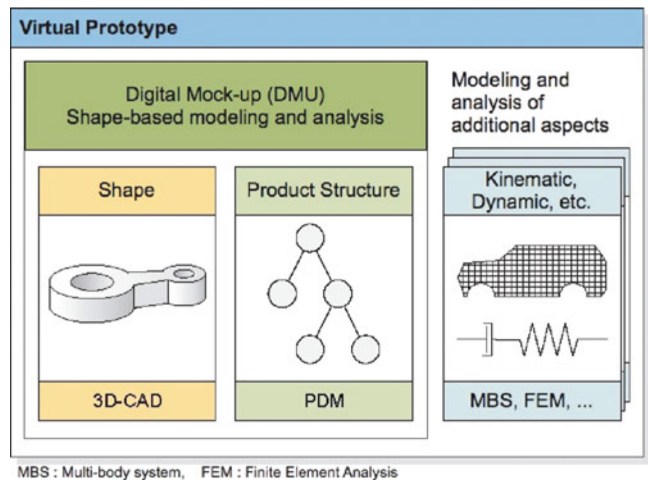

Fig. 1 Schematic representation of the term VP [1]

Today, VPs are an essential element for the development of technical products. In particular in fields, in which the products become more and more complex, like in the field of mechatronics. A mechatronic system (MS) consists of components from the domains mechanic, electric, information technology and control engineering. The complex interactions of these components, which result out of cascades of control devices, actuators, and sensors, complicate the development of a MS.

VPs help the engineers to understand the interactions between these system components. They can analyse and evaluate the interactions of the system. Thus, they can easier understand the behaviour of the product, long time before the first prototype will be build. One objective of virtual prototyping is that the engineers do not realize weather they work on a real or a virtual prototype. Until today this vanguard objective is not achieved, but the research leads into the right direction [2].

However, the build-up of a VP is a challenging task [3]. One challenge is the combination of the models, which

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represents the different aspects of the product. Normally, different developers build these models. To combine them to a virtual prototype the engineers have to identify the relations between the considered models and have to model these relations, too. Today, this is done manually, supported by graphical user interfaces only. This way makes the use of VPs difficult:

- The developers have to know very well the meaning of each variables of each model. Because every developer knows his/her model only, they have to meet and identify the relations together.
- By manual combination, the number of models is limited, which can be combined to a VP. More models increase the complexity of the VP. This results in more errors.
- Engineers have to work on the build-up of a VP. Meanwhile, they cannot focus on their intrinsic development task.

To face these problems an automatic combination of models of a virtual prototype is necessary. An approach for the automatic combination comes from the field of Knowledge Based Engineering (KBE) [4]. KBE integrates knowledge of engineers into the product development process. One objective is to automate the construction of 3D-CAD models. The approach to achieve this objective can be extended to the different models of a VP to facilitate an automatic combination of these models.

This chapter presents an approach for the automatic combination of different models in order to facilitate an automatic build-up of a VP. Semantic Web (SW) techniques are used for that purpose. Aim of the work has been to verify if SW techniques facilitates an automatic combination of different models.

In Sect. 2, the state of the art is described. Section 3 describes the approach. After this the prototypical implementation and results are explained. The chapter closes with a summary and an outlook.

2 State of the Art

Today, Virtual Prototypes are established in the product development process. However, the VPs are focused on the analysis of a few aspects only. The development and analysis of mechatronic systems demands more aspects [1, 3]. Complex virtual prototypes for that purpose are subject of current research. In the field of Knowledge Based Engineering (KBE), approaches have been developed for the automatic constructions of CAD parts. The methods of KBE are the basic for the desired purpose.

2.1 Virtual Prototypes

Virtual Prototyping means, to create a computer model of a system under development, to analyze the system and to make decisions, which are based on the VP. VPs are not new. Tools, methods and techniques are known and used in the development departments of the industry. Commercial tools are available, too. For instance, Fig. 2 shows the kinematic analysis of a robot, which has been made using a commercial tool [1].

In this example two aspects are analyzed: the shape and the kinematic. Aim is to evaluate the working room of the robot. Many other tools are available, which facilitate the analysis of the dynamic, strength, deformation or fluid flow, etc., in combination with the shape. However, most of the available tools combine two aspects only, respectively the computer internal models [1, 3].

Mechatronic systems require the combined analysis of more than two aspects [3]. For instance, if the controlled movement of a mechatronic system should be analyzed, a multi-body system, a controller and the 3D model of the system must be combined. In addition, if the system regulates the flow of a fluid, a flow simulation must be integrated into the virtual prototype, too.

VPs that consist of two and more models are subject of current research. The research focuses on two approaches: The first approach is to combine the different models. Therefore, infrastructures and methods are developed [5]. The second approach is to transform the several domain-specific models into one common domain-spanning model [6]. In this chapter, the first approach is followed.

Research in this field is carried out in the Collaborative Research Center 614 "Self-optimizing structures and concepts in mechanical engineering". The researchers have developed an infrastructure and methods for the combination of five types of models: 3D-, kinematic-, dynamic-models, controllers, information processing, and electronics. A communication infrastructure has been developed, which

Fig. 2 Kinematic analysis of a welding robot [1]

combines the models to a VP, simulates them, exchanges data between this models, and facilitates a combined analysis of them [5, 7].

A similar objective is followed in the project functionalDMU (FDMU) [3]. Within the scope of the project an infrastructure and concepts for the combination of different models are developed, too. This realizes a VP, too. The definition of FDUM is similar to the definition of a VP. A further project with similar objectives is the project GENSIM [8]. The researchers develop an infrastructure and methods for the coupling of different models, too.

However, the mentioned projects facilitate a manual combination of the different models only. The manual combination is time consuming and tends to errors. Unfortunately, the knowledge of the developers is necessary to identify the relations between the different models and to combine them.

2.2 Knowledge Based Engineering

The term KBE comprises methods for the integration of knowledge into the process of construction [9]. This knowledge should be available for the engineers during the construction process. One objective is the automatic construction: KBE systems assist during the construction process by suggesting parameters or features, or by constructing or optimizing the shape of the entire part [4].

Today, KBE methods and techniques are available in commercial CAD software tools. In addition, several companies offer KBE modules, which can be integrated into common CAD software tools. These modules respectively their functions solve common construction tasks, e.g. the specification of the dimensions of feature elements like fitting keys, or they optimize the shape of a spindle.

Methods for the representation of knowledge are expert systems or semantic networks. Expert systems depend on a knowledge basis; a database, which contains the knowledge. A reasoning mechanism is necessary to request the knowledge from the database. This mechanism transforms data into knowledge. Semantic networks are a conglomeration of different items and relations between these items. Items and relations form a graph; items are the nodes, the relations represent the edges. Thereby, a formal knowledge model is build. Semantic request are used to query the knowledge.

Most of the research in this area focuses on the improvement of KBE in order to fulfill one concrete optimization task. For instance, Klette et al. have developed a method for the optimization of the shape of mechanical parts under consideration of the production complexity and costs [10]. Drupt et al. have developed a KBE method for reverse engineering [11]. One aim of their work was the automatic construction of rudimental wireframe models from point clouds.

However, the main focus of KBE lays on 3D-CAD models and their automatic construction and optimization. But the techniques and methods like semantic networks and the related reasoning mechanisms can be used for the automatic combination of different models, too.

2.3 Semantic Web and the Resource Description Framework

One famous application of semantic networks is the Semantic Web (SW). The SW facilitates machines to "understand" the content of web pages and other similar documents [12]. Thus, the machines can automatically link the information of different sources.

The Resource Description Framework (RDF) plays a decisive role for the SW. RDF is a description language, which is used to annotate the content of a web page; it is syntax for meta data of a web page. The underlying model is based on a directed graph. The nodes of the graph are denoted as resources, the edges are denoted as properties. The idea of RDF to is describe complex facts by a network of simple RDF statements. A RDF statement consists of a subject, a predicate and an object. Figure 3 shows an example. It shows an RDF statement, which describes a digital business card of a person named Karl Mustermann.

The subject is an Unified Resource Identifier. It is linked to the data of the business card. The object is the name of the person, who is related to the business card. The predicate expresses the relation between the subject and the object. Here the predicate vc:person is used. The predicate is the most important thing of the semantic. It is a W3C (World Wide Web Consortium)-standardized predicate for the description of business cards. The SW works only, if everybody has the same understanding of these predicates and interprets them in the same manner.

A reasoning system is necessary to identify relations between two RDF-annotated web pages. RDF represents the database only. For that purpose query languages are used to query the necessary information. The queries need to be prepared in a way, that reasoning is possible. Therefore, queries like select [object] where [predicate] as well as a set of if . . . then clauses are used.

Some researchers have already used RDF and the related reasoning mechanism for the KBE of mechatronic systems.

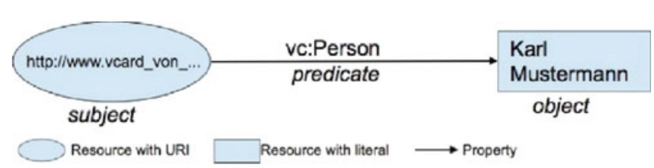

Fig. 3 RDF statement of a business card

For instance, Bludau and Welp have developed a framework, which supports engineers during the development of mechatronic systems [13]. Their framework searches for active principles and solution elements, which meets a given specification. Restrepo uses the SW techniques to search for design solutions for a given problem [14]. He has developed a database, which contains different design solutions; every solution is annotated by RDF. A reasoning mechanism searches for solutions, which meets the given design problem.

RDF and reasoning mechanism from the field of SW do not have been used for the automatic combination of different models. The approaches from KBE and the SW can be taken and be used for the development of a Semantic Virtual Prototype.

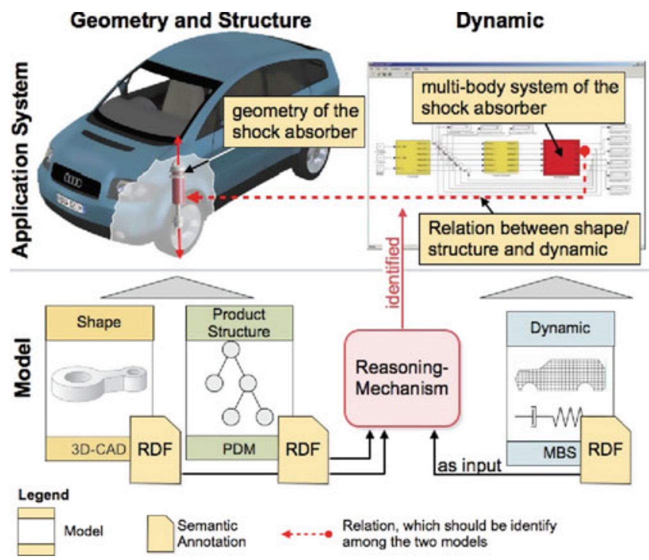

Fig. 4 Concept of the automatic combination

3 Semantic Virtual Prototype

A Semantic Virtual Prototype (SVP) is defined as computer internal representation of a real prototype, at which the meaning of the single models and its attributes are annotated by a semantic description. Aim is to integrate the meaning of the models into the computer internal description in order to facilitate an automatic combination of different models and an automatic analysis of interactions between them.

This chapter answers the questions if SW techniques facilitate a combination of different models from technical domains. It focuses on two kinds of models: 3D models and multi-body systems. The latter represents the movement of the 3D model. Next, the concept is described. Then the semantic annotation of a 3D model using RDF is presented, followed by the semantic annotation of a multi-body system. Finally, the reasoning mechanism is described, which identify the relations between both models.

3.1 Concept

Figure 4 presents the concept of the SVP and the automatic combination of different models, using the example of the shape of the product, its structure and a multi-body system (MBS), which represents the behavior. The figure is divided into two regions. At the top the view of the application systems (CAD, simulation application) is presented. The view of a CAD system visualizes the computer internal model of the shape as 3D model. The simulation application visualizes the MBS as block diagram. At the bottom several icons represent the related computer internal models.

In the following, the automatic model combination is explained by the example of a shock absorber. The 3D model of the absorber should be combined with the multi-body system, which represents the behavior of the shock absorber. To realize the link, attributes of the multi-body system must be linked with attributes of the 3D model. The dashed line in Fig. 4 points out this link.

To achieve this, the models become semantically annotated with RDF. A reasoning mechanism identifies attributes in every model, which have the same meaning. In the example the reasoning mechanism needs to find the horizontal movement axle of the 3D model and the variable from MKS model that describes this movement.

To realize this, several questions are to answer:

1. Which items of a 3D model and a MBS model should be annotated?
2. Which vocabulary should be used for this annotation?
3. How must the reasoning mechanism work and which evaluations are necessary?

The following sections answer these questions. The presented example shows a section of a real RDF model only. Furthermore, one attribute is used only. A real RDF description of a model is confusing and would complicate the following explanation.

3.2 Semantic Annotation of the 3D Model

To describe the purpose of a 3D model, the items of this model need to be described, which are responsible for the functionality. Pahl/Beitz [15] as well as Albers et al. [16] have carried out researches about these items. Their work is used as basic for the RDF description of the 3D model.

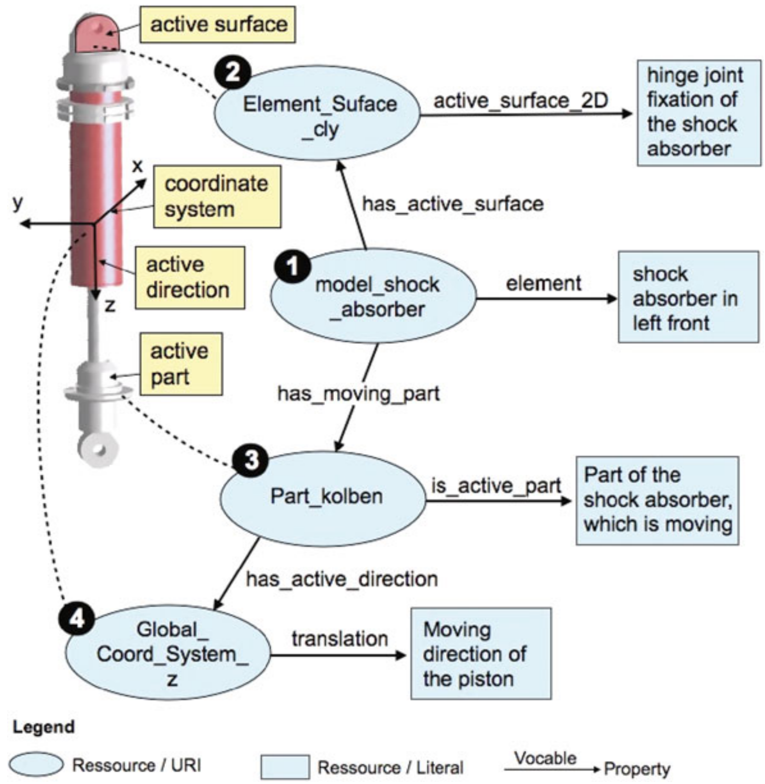

Fig. 5 Semantic description of a 3D CAD model

Figure 5 shows the 3D model of the shock absorber and its annotated items. The symbols in the figure show a graphical representation of an RDF-based semantic annotation. Four items are annotated: the entire part, the active surfaces, the sub-parts and the active directions.

First, the entire part is described (Fig. 5 (1)). The resource is linked to the variable, which is used to represent the model inside the CAD system. Here it is the variable *model_shock_absorber*. The variable is annotated by the predicate element. To describe the element, a literal is used. In this example it describes the part as *shock absorber in front left.*

The second annotated type of items of a 3D model is the active surface (Fig. 5 (2)). The active surfaces of a component are the surfaces, which fulfil the functions of this component [15]. At an active surface the component is coming into contact to an active surface of another component. Each component fulfils its function only by the contact to another component. According to the principles of Albers et al. [16], the metaphor of active surfaces can be transferred to liquids or electrical components like sockets, too. Thus, hydraulic components or electrical sockets can be annotated, too.

An example of the RDF description of an active surface is shown in Fig. 5 (2): The resource is linked to the active surface of the component. Therefore, the variable is used, which describes this surface in the data structure of the 3D CAD model. In the example, the name of the variable is *element_surface_cly*. As predicate the word *active_surface_2D* is used. We have defined a set of words to describe active surfaces. The words classify the active surfaces according to their shape (2D, 3D), type (point, line, surface), and their location (surface, parallel surface, etc.). The purpose of the active surface is described by a literal. In this example, this literal describes the active surface as *hinge joint fixation of the shock absorber.*

Third, the semantic annotation describes the structure of the 3D model. Today, most of the CAD software tools do not only represent single components in one model, they represent sub-assemblies or the entire assembly of the virtual product. Thus, the single components of an assembly need to be described by a semantic annotation. Particularly, if some components of a sub-assembly are active components, they must be distinguishable from the passive components. Active means they move to effect the function. An example of the semantic annotation shows Fig. 5 (3). The resource refers the variable, which describe the main part in the data structure of a CAD system; here it is the entire shock absorber. The word *has_moving_part* is used as RDF predicate. The predicate refers to the part of the sub-assembly respectively to the name of the variable, which describes the part in the structure of the entire 3D model; the variables name is *part_piston*. Eight words have been defined to describe the structure of an assembly. Every word specifies another kind of relation. The most important words are: *has_moving_part*,

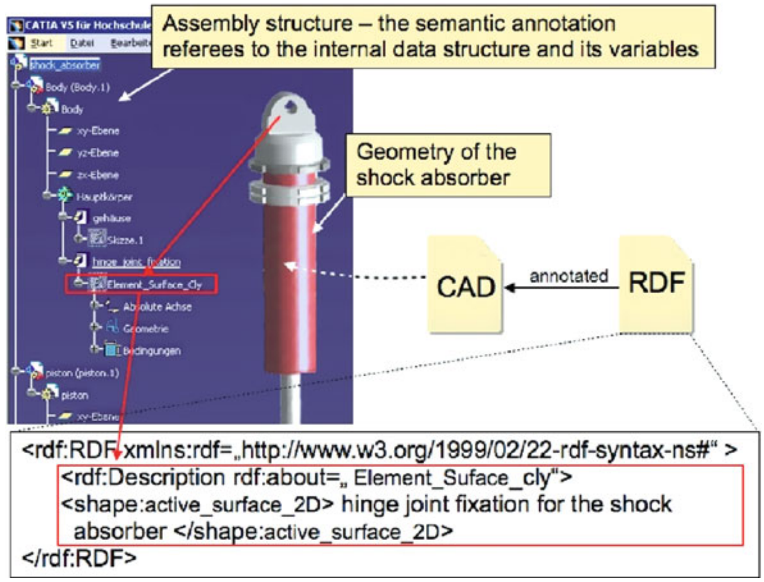

Fig. 6 The semantic description is stored in RDF/XML notation into a separate file

has_socket, *has_static_part*, and *has_joint*. In our tests of the automatic combinations of models, we were able to specify every sub-part of a 3D model using these words. Additionally literals were not necessary.

Furthermore, to describe this active part, a predicate *is_active_part* is used. This word denotes this part as part, which affect the function. Additionally, it facilitates the annotation with a literal. In this case the literal contains: *Part of the shock absorber, which is moving*.

The fourth annotated type of items is the active direction (Fig. 5 (4)). According to Pahl/Beitz [15] the active direction describes the direction, into which a function of a component effects. The active direction results from the alignment of the active surfaces. To describe them the RDF resource refers to the variable, which describe the coordination axis of the active part. In Fig. 5, the piston of the shock absorber is the active part, which active direction should be described. The variable *global_coord_system_z* describes the coordinate system; it describes the direction of moving. It is attached to the resource *part_piston* by the predicate *has_active_direction*.

In addition, the resource *global_coord_system_z* need to be annotated with a human understandable literal. In the example, the literal says *Moving direction of the piston.* It is attached to the resource by the predicate translation. It indicates that the literal describes a translation. Other words for the description of an active direction are *rotation*, *oscillation*, *ramp*, and *jump*.

The entire description shows one example only. The example should give an impression, how the semantic annotation with RDF works and which elements of a 3D model are necessary in order to describe the purpose and functionality of a 3D model in a natural way (literals). Altogether 36 RDF words were defined to describe the active surfaces and directions as well as the parts/sub-parts of an assembly.

A user can specify the literals by it's own. But two conditions need to be satisfied. First, every literal must describe the part and its function in a general understandable way. No shortcuts, metaphors, slangs, etc. are allowed. Second, the user is asked to use one or more sentences. No short terms or single words are allowed.

The semantic annotations, which are described in RDF are stored to a XML file. Figure 6 shows an example of the XML-based RDF description.

The figure shows the semantic annotation of the active surface. The line <rdf:Description rdf:about="Element_Suface_cly"> refers to the variable, which describe the active surface in the data structure of the 3D CAD model. The next line shows the literal *hinge joint fixation of the shock absorber* and specifies it as an *active_surface_2D*.

The description is not integrated into the file, which contains the 3D model. A second file is created. This file contains a reference to the file of the 3D model.

3.3 *Semantic Annotation of the Behaviour*

The second model, which is used in this work represents a multi-body system (MBS). Analogous to the 3D model, the items of the MBS need to be semantically annotated, which describe the functionality of the modelled product. As basic for the selection of the items, the semantic vocabulary, and the necessary structure of the model, we used research results from the collaborative research centre 614, where the manual combination of different models has been analyzed [5]. Furthermore, we could extend results from Welp et al. [13]

and Hahn [17]. Welp et al. have suggested an approach for the coupling of MBS, too, similar to the approach described in [5]. Hahn developed a data model for the formal description of MBS. These researches are the basis for the following description.

Annotated are two items: the assembly, which is described by a set of rigid bodies, and the relations between the rigid bodies. One advantage that occurs during the work on the description of MBS was that MBS, their attributes, and the meaning of these attributes are well defined. The items of dynamic and kinematic models are good documented and limited to a small set of elements. For example, if a kinematic model should be described, rigid bodies and joints between these bodies are used. The set of joints is well known and limited: e.g. ball-and-socket joint, hinge joint, cardan joint, etc.

In the following, the semantic annotation of the two items of the MBS is explained. The shock absorber mentioned before is used as example, too.

First, the (sub-)assembly of the product is annotated. Figure 7 shows an example of the semantic annotation of a computer model of a MBS system. Here, the approach supposes that the items of one technical sub-assembly or one component are combined to one group. Most software tools for the modeling of MBS allow grouping of single elements to subsystems. Each subsystem is presented as a single block. The block has input and output channels, which represents the technical values like forces, torques, electrical flow, etc. The block in Fig. 7 represents the MBS of the shock absorber.

On the right side of Fig. 7 the related graphical representation of the RDF annotation is depicted. The block itself has a variable; its name is *shock_absorber*. To annotate the block, the RDF resource references the name of the block (1). The subject is annotated by the word element and it refers to a literal. The literal contains a natural language description of the block: *Shock absorber at left front.*

Second, the relations between the blocks are annotated. The single inputs and outputs of the block diagram represent these relations. Each relation is a technical value like a force, torque, velocity, position, or another technical value. One output of the shock absorber is the elevation of the piston. The variable *h* describes this elevation. To annotate this variable, a RDF resource refers to this variable (Fig. 7 (2)). The predicate *translation* connects the resource with a literal. The literal contains text, which tells the meaning of the variable *h* in a natural language: *Elevation of the piston*. Additionally, the entire RDF expression (2) is linked to the description of the block (1). Therefore, the predicate *has_output* connect the two resources.

A similar description is used to annotate the input values of each block. In our example, a force effects to the shock absorber, the name of the variable is *F_active*. To annotate the input, a resource refers to the variable *F_active* and a predicate link the resource to a literal. As predicate the variable force is used. The literal describes the object as: *Force that effect to the shock absorber.* In addition, the RDF expression (3) is linked to the resource, which describes the block (1) in order to express the relation. Therefore, the predicate *has_input* is used.

Twenty eight predicates are defined to describe the inputs and outputs of the blocks. These are predicates like: *force, torque, position, velocity, acceleration, time, frequency, trigger pulse, energy*, and some more. Every word describes a technical dimension.

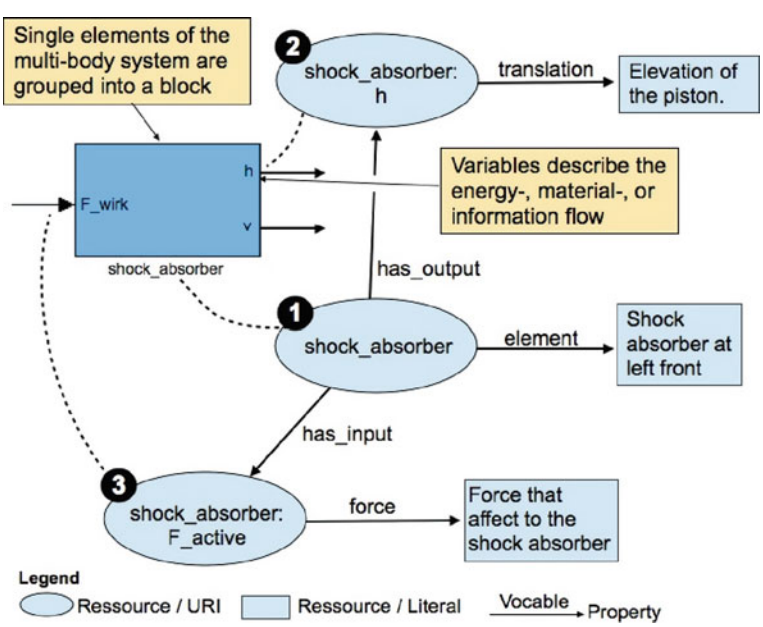

Fig. 7 Semantic annotation of a multi body system

The literals describe the meaning of the inputs and outputs in a natural language. Similar to the literals used for the annotation of the 3D models, the annotation should consist of one or more sentences and no shortcuts or slang are allowed. Apart from that, the user can select the content by his/her own.

The RDF description is stored in XML notation in a separate file. Integration into the file of the MBS is not possible, due to the close data definition of that files. The XML file keeps a reference to the file of the MBS.

3.4 Reasoning

A reasoning mechanism is necessary to determine the relations between the 3D model and the MBS. The reasoning mechanism contains a set of rules and queries, which are used to create "knowledge" – knowledge in the context of SW means that a computer is able to process data automatically.

To determine the relations between the two models, four steps are necessary:

1. Search for corresponding predicates
2. Statistical phrasal analysis of literals
3. Element identification
4. Ranking and Decision

The procedure and the methods, which are used in the steps, are standard methods in the field of SW (see [18]). A text mining method is used to find similar statements in the literals. In addition, a backtracking algorithm searches for similar elements in the RDF description. A probabilistic function calculates the similarity-value.

Figure 8 shows the principle of the used reasoning mechanism. The RDF files, which contain the annotation of the 3D model and the MBS are the input for the reasoning mechanism. Two statements of the example of the shock absorber are used to explain the mechanism.

Step 1: In the first step, corresponding predicates are searched in both models. As corresponding predicates each pair of predicates is defined, which describe the same common meaning of an item. Figure 8 shows an example. The top of the figure shows a section of the RDF description of the 3D CAD model. The bottom shows a section of the RDF description of the MBS; both in graphical RDF notation. The predicate translation in both descriptions is such a predicate, because its semantic means a movement of an item. Which pair of two words forms a corresponding pair is defined in a heuristic. The heuristic contains pairs of corresponding words. For instance, the mentioned words *has_output* and *has_active_direction* form a corresponding pair, too. At

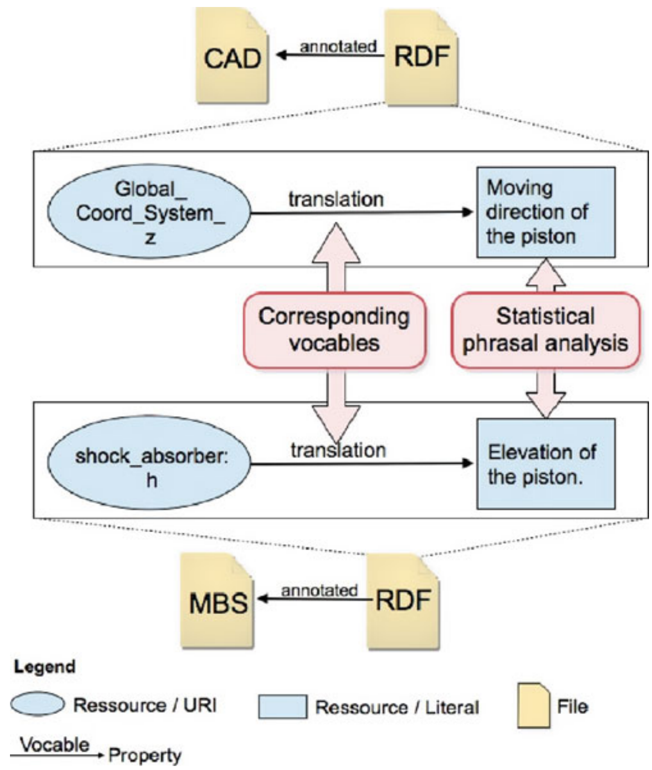

Fig. 8 Principle of the reasoning system

this time all the pairs are defined by commonsense. During further development, we want to replace this set by a self-learning system. The result of this step is a list $L_{\text{correspond}}$, which contains all the indentified corresponding predicates. The entries are the starting point for the next step.

Step 2: In the second step, the literals of each corresponding pair of predicates are compared. This is done by a statistical phrase analysis [18]. The phrase analysis determines whether the content of the literals meets each other or not. It calculates two vectors l_1 and l_2, each vector represents a literal as a numerical description (for details about the method see [19]). The similarity is represented by a numerical value V_{similar}. 0 represents no similarity. If V_{similar} is 1, the content of the literals are similar. It is calculated by a cosine calculation, known as cosine degree:

$$V_{\text{similar}} = \cos(l_1, l_2) \tag{1}$$

The analysis is carried out for every entry in the list $L_{\text{correspond}}$.

Step 3: In the third step, the element of each corresponding pair is searched for. An element is the main component, which is annotated by the word element. In our example, it was the shock absorber. As mentioned before, the example shows only a small section of a real RDF model. Normally, it forms a complex network with many elements and many different sub-parts.

In order to find the element a backtracking algorithm is used. The entire RDF description represents a graph. We assume that the element is placed at a higher position (back) of the graph, because the set of corresponding words are defined in a way that the corresponding words should occur close to the leaf nodes of the graph.

If the elements in the RDF graph of the 3D model and the RDF graph of the MBS are founded, a statistical phrase analysis is performed with the literals. It is the same analysis, which is performed in step 1. The result is a value E_{similar}, calculated with Eq. (1), too. Its value shows the similarity, where 0 indicates no similarity an 1 indicates similarity.

$$R_{\text{similar}} = V_{\text{similar}} \times E_{\text{similar}} \tag{2}$$

This calculation and the entire step 3 are performed for every entry i in the list $L_{\text{correspond}}$. The results $R_{\text{similar},\,i}$, where i indicates the entries, are stored in a second list L_{Result}. Each entry represents a possible relation between two elements.

The step is necessary, because in every RDF model contains multiple equal corresponding pairs of words. In our example, the car has four shock absorbers. Each shock absorber is annotated with identical words. The only differences between these four shock absorbers can be found in the literals, which describe another position of the shock absorber, e.g. “front, left”, or “front right”.

Step 4: In the last step, the relations between the 3D model and the MBS and their attributes have to be determined. Input for the last step is the list L_{Result}. In order to identify the relations, a probability value $p(j)$ is calculated for each value. Therefore, the statistical method of squared ranking is used: Based on its value $R_{\text{similar},\,i}$, it expresses each entry i with respect to the anticipated number of combination between the two models. The probability is calculated by:

$$p(j) = \frac{1}{\text{size}} \cdot \left(E_{\max} - (E_{\max} - E_{\min}) . \frac{(R_{\text{similar},j} - 1)^2}{\text{size} - 1} \right) \tag{3}$$

where j is the position of each value $R_{\text{similar},i}$. The values $E_{\max}$ and $E_{\min}$ are values, which express an anticipated number of relations, it is estimated by the user; size indicates the length of the list.

The result is a list, which contains the probability of each possible relation. Every detected pair of RDF expressions and its resources, respectively the referred variables, are determined as similar relations, if they fulfil the equation:

$$p(j) \geq p_{\text{Threshold}} \tag{4}$$

$P_{\text{Threshold}}$ is a threshold value; the user has to decide by its own, which value is adequate. This should be done interactively with visualization support. The user needs to review the resulting relation while changing the threshold.

4 Results

The described method has been implemented and tested. The implementation is prototypically, aim was to prove, if the method is suitable for the desired purpose.

4.1 Prototypical Implementation

Following tools have been used: 3D CAD models have modelled with CATIA V5. The CATIA assembly module facilitates to arrange several 3D models in space and provides a structure of the model. For the further steps, the CATIA model needs to be exported into a VRML model. The structure and the single model as well as given variable names are kept in the VRML model. The VRML model is loaded into a 3D-Viewer. The viewer is a self-developed tool. It is based on the 3D programming library OpenSceneGraph (www.openscenegraph.org). An own viewer was necessary, because CATIA do not allowed to create the necessary links for the combination of two models in its data structure. Essential for the test was, that the 3D models, the product structure and the names of the elements in the structure are kept and reused. This could be assured. The coupling of the two models itself is performed by TCP/IP communication.

The MBS have been modelled with Matlab/Simulink. Simulink facilitates to model a MBS as a flow diagram. The needed sub-block hierarchy is available, too. It is necessary to encapsulate MBS of a single component like the shock absorber into a block. For our tests we use the Matlab Real-Time Workshop (RTW). RTW exports code of the model. The exported model can be simulated. The variables and its data, which are related to the items of the 3D model, are submitted to a communication server.

The technical aspect of the combination of two models are described in [20] and [21]. A communication server is used for that purpose. Matlab/Simulink and the 3D-Viewer have a self-developed plug-in in order to connect to the server and to exchange the necessary data.

For the annotation of the models the software SchemaAgent from Altova is used. It provides a graphical user interfaces to model the resources, properties and the entire RDF graph. The RDF model is stored in an XML notation.

The software library Jena is used to implement the RDF vocabulary for the annotation, the RDF queries, and the reasoning system (http://jena.sourceforge.net/). Jena is a framework for building Semantic Web applications. It provides a programmatic environment for RDF, RDF-Schemas and includes a rule-based inference engine. The inference engine has been extended to realize the method, which is described in Sect. 3.4. But the basic algorithm and methods to process RDF and compare multiple RDF descriptions are included.

4.2 Results of the Automatic Combination

To test the method two different virtual prototypes respectively their models have been. The first VP was the car, which have been used as example in the sections before. The model contains the most important parts for the test of the movement: the shock absorbers, the wheels, the chassis, the doors, and the body. The second system is a mechatronic suspension-and-tilt module for a train system. For each system, a 3D model and a MBS system have been prepared. The number of variables in both models was fixed to 30. This makes the test more comparable. Every model have been prepared and annotated by a different person.

A total of 36 tests were carried out. At each test, the values E_{max} and E_{min} have been varied. At the end six different persons have annotated the models with different literals.

Figure 9 shows the results of three tests in detail. In these tests, the relations between the 3D model of a car, its components, and the items of the multi-body system should be found. The main elements, which relations need to be identify were two shock absorbers, two dimensions of the body (x,y), two doors (open/close), and two wheels (rotation). The abscissa of the diagram shows possible relations between the two models respectively their elements. Each entry of the abscissa represents one possible relation; the entries are the results in the list L_{Result} (Sect. 3.4). But only the first 30 of the 435 possible relations are presented. The ordinate shows the probability p, which is calculated by Eq. (3). The three lines show three results. Each line shows a result with different E_{max} and E_{min} values.

The first eight variables on the abscissa represent the main relations, which should be found. The probability for these variables is between 71 and 89%. This shows that the method is able to identify the desired relations between the two models. One interesting effect can be observed. The probability curve shows a sharp decline, after the desired eight relations have been identified. This sharp decline of the curve could be used for automatic detection of the threshold in Eq. (4). For now, it demonstrates the suitability of the approach: the probability curve shows a distinctive feature, which separates the desired relation between the models from the others variables and features in the models.

All in all approximately 80% of all desired relations could be clearly identified in the 36 tests. The other results do not show a distinctive feature like the sharp decline of the probability p, which makes it difficult to identify the relations.

5 Summary and Outlook

In summary, the tests show that SW techniques facilitate an automatic identification of similar elements of two models. The decision, which variables from the two models have to be linked in order to realize a virtual prototype, is made automatically. Three things could be shown in this work:

First, a set of items of a 3D model (like the active surfaces) and a MBS system has been identified for the semantic annotation with RDF.

Second, the attributes and dimensions, which are known from literature to describe the items of the models in a domain-specific language, can be transfer to a vocabulary for RDF.

Third, a reasoning mechanism is possible, which works with the RDF description and the vocabulary. The reasoning mechanism can identify the relations between the models. These relations are the starting point for the automatic combination of the models. The referred variables need to be linked only. Therefore, every communication infrastructure can be used.

The results are a good starting point for further research. As mentioned before, aim is to couple multiple models to

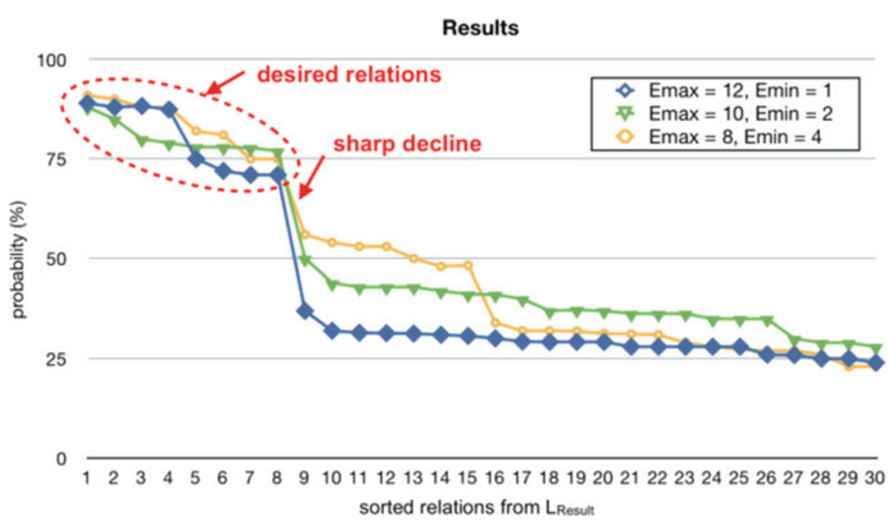

Fig. 9 Three results of the test

a virtual prototype, not only two. Next, the domain control engineering respectively controllers and the domain electronics will be considered. A RDF formalism and the necessary vocabulary will be defined.

The shown approach is limited to a specific kind of modelling. CAD engineers have to define a well-structured assembly. The MBS model needs to be structured in sub-blocks, where each sub-block groups all elements of a model. When an engineer does not follow the desired principles of modelling, it can be assumed that the approach will not be able to identify the related elements and its variables in the two models. This is what needs to be proved. Therefore, some tests are planed where different engineers should annotate their own models. The engineers are members of the collaborative research centre (CRC), in which scope the presented method is developed. Due to the results of these tests, the RDF description will be adapted. If it could be pointed out, that most of the engineers follow a similar strategy for modelling, and the RDF description is suitable to annotate the models, then we will keep the method. Otherwise, it will be adapted it in a way, that we cover most of the design strategies.

Furthermore, an automatic learning method is planed that learns the corresponding set of words, mentioned in Sect. 3.4. Now the corresponding words are selected by commonsense. The results show that the selection seams to be good. But the static selection can have had influence the results of the test. If the set has been chosen to narrow, the set cannot be used in general. Then it will work only for our two tested examples. But if the set is too large, the relations between the models can only be found, if the annotation of the models is definite expressed. Normally, a definitive semantic annotation cannot be assumed. At the CRC we are convinced, the two different tests show that the set is well selected and not limited to two models only. At last, the last doubts can only be eliminated with an automatic learning method.

One further work is to integrate an ontology. The ontology is necessary to identify different words in the annotation, which have the same meaning. During this work the involved people have agreed a thesaurus for the nouns and the verbums. This thesaurus will be extended to an ontology to facilitate a domain-spanning understanding.

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Application of PLM Processes to Respond to Mechanical SMEs Needs

J. Le Duigou, A. Bernard, N. Perry, and J.-C. Delplace

Abstract PLM is today a reality for mechanical SMEs. Some companies easily implement PLM systems but it is more hazardous for SMEs. This chapter aims to explain why some of them do not success to integrate PLM systems. This analysis is based on the needs of the SMEs in the mechanical domain, the processes that respond to those needs and the actual PLM software functionalities. The proposition of a typology of those companies and the responses of those needs by PLM processes will be explain through the applications of a demonstrator applying appropriate generic data model and modelling framework.

Keywords Product lifecycle management · Product-process modelling · Information system

1 Introduction

Due to globalisation, the enterprises have to work in networks more and more diversified and geographically dispersed. To reach cost, quality and delay optimisation, enterprises implement new information and communication technologies. The mechanical SMEs adopted this logical, but, even if they are more flexible, they face difficulties in the information exchange and share.

PLM systems are a solution to structure and share product information. Nevertheless, in 2007, only 3% of those enterprises have implemented such a system [1, 2]. Our hypothesis is that the functionalities of the actual systems do not fit with the real needs of those users.

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This chapter introduces first the functionalities of PLM systems. The next section explains our research approach based on a bottom up approach: first a practical immersion and solution development is done in three specific cases selected within a PLM oriented enterprise's typology. Then, a conceptual work begins, the needs from these samples are aggregated, their processes solutions are formalised. Finally a demonstrator, based on a generic model, is developed to validate the global solution proposal. Discussion and perspectives conclude this chapter.

2 PLM Processes

CimData [3] define the PLM as *a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination and use of product definition information across the extended enterprise from concept to end of life – integrating people, processes, business system, and information*. The actual definitions of PLM [4, 5] focus on the product data, but do not include the processes management notion. To improve that point, the following definition centred on the activities is proposed: *PLM is a business strategy to manage on a collaborative way the product centred activities during the whole lifecycle and across the extended enterprise.*

PLM encompass not only the definition of the product, but also the definition of the product lines, of the technologies used, of the organization, of services associated to the product (services during its use, but also during its maintenance, its end of life…). In a mechanical SMEs context, the production lines are not redefined with the creation of a new product. SMEs have to produce new products with the existing capacities and machines, which is not the case for the firms from automobile or aeronautical sectors where a new production line can be created for the creation of a new product. It is quite the same for technologies used and the organization that do not change with the arrival of a new product. The services are not taken into account by mechanical SMEs, maybe because they are not yet in

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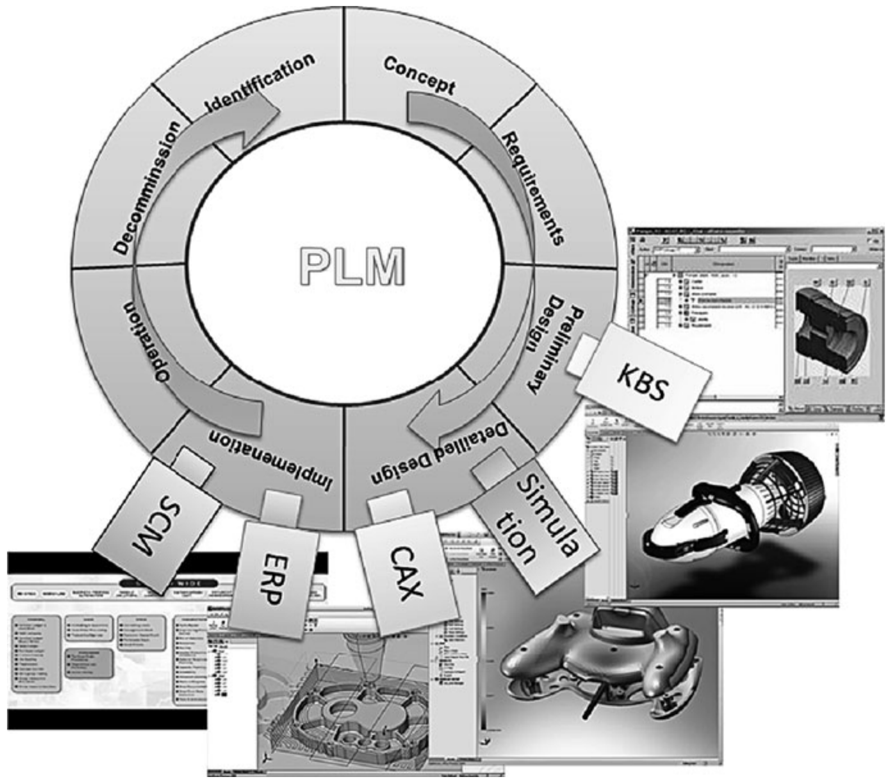

Fig. 1 PLM and business software

charge of the maintenance and end of life of their products or because they have to manage the definition of their products before managing their maintenance or their end of life.

PLM is supported by business software. The PLM systems help to pass the product definition information from one business solution to another (Fig. 1). Interoperability and modularity are important issues in those systems [6]. It encapsulates and then diffuses the information for the product development. It is realized by links between the PLM systems and the other software (Fig. 1), as CAD, CAM, ERP, SCM... Moreover it ensures the traceability [5], the archiving [7] and the reuse [8] of information.

The PLM systems offer numerous functionalities, the most classical are:

Vault: The data and documents are stoked in a server. The data are stoked in a database and structured through the data model implemented in the database.

Right access: The user must have sufficient right access to operate on the data (read, modify, validate...).

Check in/check out: The user must check out the document before modifying it. Then he checks in the modified document. This assures that two users cannot modify a document at the same time.

Versioning: It traces the change of a document or a data. At a second level, a revision serves to trace major modifications.

Notification: Notification is the sending of an email with a link to the data or document subject of the email. Automatic notification for change, validation... is called subscription.

Workflow: This system simulates processes and automates some activities of the process. It is principally used for documentation processes like validation.

State: They are associated to document and define their maturity level (creation, in validation, validated, obsolete).

Actual tools are mainly dedicated to documentation and communication management. The possibility to automate and manage activities more business oriented is not in the actual functionalities. SMEs are looking for more advanced business or management functionalities.

Notice that the majority of the works done on PLM are related to firm, often automobile or aeronautic assemblers [9–11]. Deductive approaches are used to integrate SMEs in the assemblers' point of view. An inductive approach will be more appropriated to include SMEs needs.

3 Research Approach

We aim on the one side to propose processes and functionalities appropriated to SMEs and on the other side, to structure and to exchange product information. Our approach inverses the traditional V cycle. It starts with a first inductive and

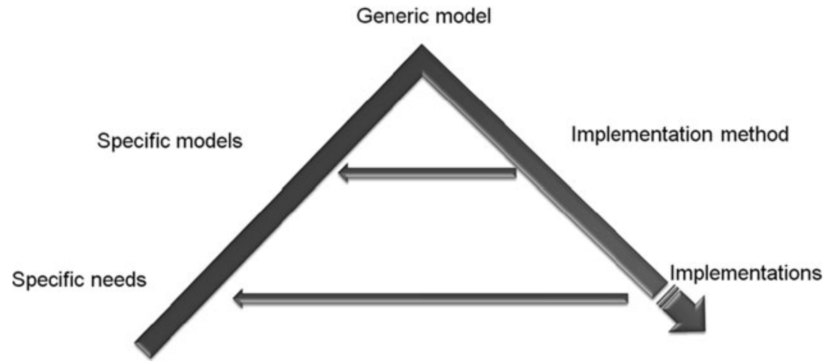

Fig. 2 Research approach

raising step to formalise the needs and the processes to implement. The second step is deductive and downing to validate the propositions (Fig. 2).

From the diversity of the mechanical SMEs, this section proposed a typology to class those enterprises in function of their PLM problematic.

The main technical information link to the product development to manage at an enterprise level is in the Bill of Materials (BoM) and in the routings. The predominant use of one or the other intermediary object depends on the number of components per products of the enterprise.

Indeed the enterprises of which the products have numerous components work on the assembly of sub-systems. The product information are then in the BoM. For the enterprises in which the products have few components, they work on the manufacturing of the parts. The product information are then in the routings.

So the proposed enterprise's typology has as differentiation axis with the number of components per product. The different companies are grouped according to the number of components of the products that they design and/or produce (Fig. 3).

Three types of companies are obtained:

- The companies producing equipments.
- The companies producing components.
- The companies producing craft parts.

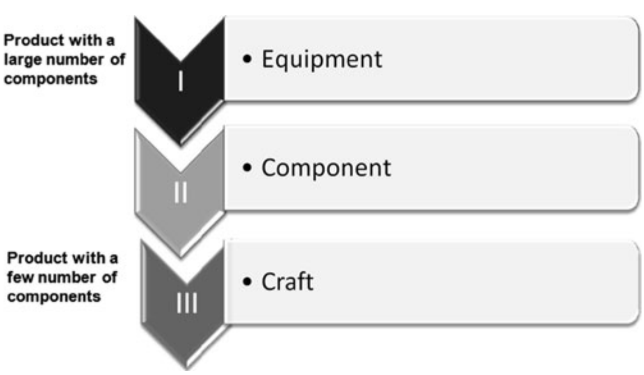

Fig. 3 Typology of mechanical SMEs

The equipment manufacturers are companies in which the products contain numerous components. They produce special machines, agricultural machines, stevedoring machines... They have problematic about BoM management and traceability, well known of the PLM systems because they match to the needs of the automobile and aeronautic sectors. The solutions to implement are lighter and less complex than the big firms' solutions.

The component manufacturers are companies of which the product contains a medium number of components. These enterprises design and/or produce compressors and motors, tools, transmissions (hydraulic, mechanic or pneumatic)... They have various needs from the customer needs analysis to the manufacturing.

The craft parts manufacturers have a few components in their products. They produce discrete parts from the forging, foundry, machining, drawing... These enterprises have problematic about the routings management.

After applying the approach on the three different kinds of enterprises, the result is three needs' maps, three processes models and three data models [12, 13]. The aggregation of those results allows to define a generic model for the mechanical SMEs (Fig. 4).

4 Application of PLM Processes

4.1 Identification of the Needs

The main problems of each enterprise were identified in [12], and detailed in [13]. A list of PLM needs is created from those immersions, focusing one those that are not fully implemented in the actual PLM systems.

Following our study, six classes of needs are identified:

Configuration management: It comes from the equipment part manufacturers. The PLM systems must manage the alternatives, the options, the versions, the families and the differentiation between internal and external products.

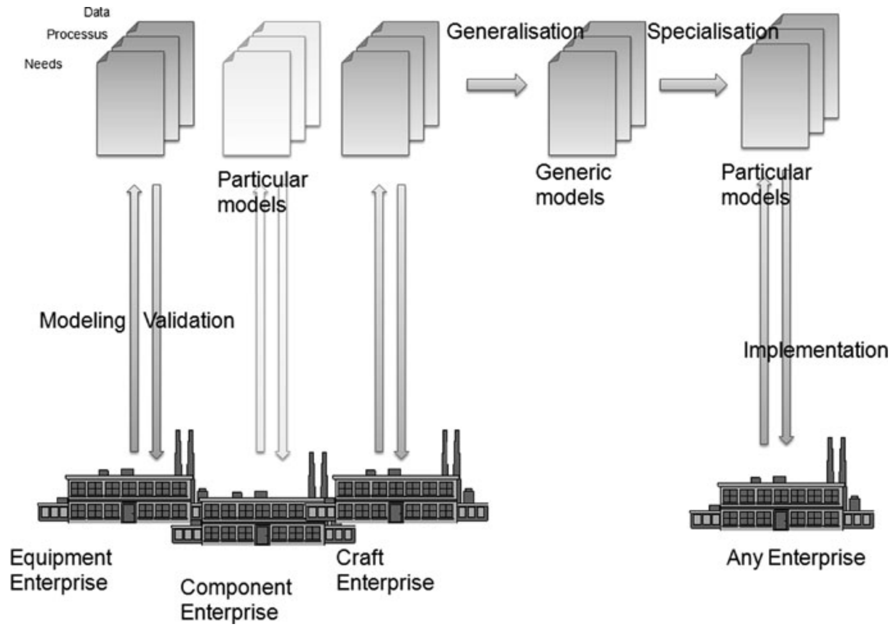

Fig. 4 Generalisation approach

Collaboration: The exchange with the customers (for the parts and components manufacturers) and with the suppliers (for the components and equipments manufacturers) must be facilitated and standardized, especially for the CAD files exchanges.

Multiple views: The information has to be visible with the structure and the names of each department. It is particularly need for the BoM in design and production departments, corresponding to the structures of the CAD and the ERP software.

Routing management: The raw parts' manufacturers need that the routings and the whole information that it includes (operations, work centres, tools...) could be managed from the PLM systems.

Interoperability: The interoperability with the ERP and the CAD is asked from the three types of SMEs, especially for the BoM and routing updates.

Decision aid indicators: The cost is the most asked indicator, to choose between alternative products for the equipments manufacturers or to choose between alternative operations in a routing for the raw parts manufacturers.

Those needs have to be resolved by the PLM systems to interest the mechanical SMEs. The processes implemented in the pilot enterprises solve those needs. The generalisation of those processes should help to solve the generic needs.

4.2 Formalisation of the Processes

The processes covered by the pilot companies could be aggregated to represent a complete development product in an extended enterprise.

The required level of detail of the SADT makes appear the intermediaries. To know the processes of creation, use and decommission of those intermediaries in the information system, it is necessary to know those processes in the real life with the same level of detail.

Moreover it is necessary to reach this level of detail in the three companies to be able to generalize appropriately the processes. Indeed the same intermediaries are in several companies, continuing their life cycle passing from a company to another. This exchange of intermediaries allows linking the processes from one company to another, like in an extended enterprise.

The global process is a development process. It includes the need analysis, the design and the industrialization. The production, the sale, the distribution and the end of life of the product are not covered by this process which is focused on the SMEs context. As explained previously, the mechanical SMEs do not express the wish to include those processes.

To manage those processes, an appropriate data model is required. The objects to be included into the data model are those used by the processes and which appear as input and output of the activities.

4.3 Realisation of the Processes

The model generalizes the objects used in the pilot companies to obtain generic objects. The semantic alignment was the principal difficulty. One object can be named differently depending on the enterprise. The fact that one consultant has done the three models makes easier the concatenation of the

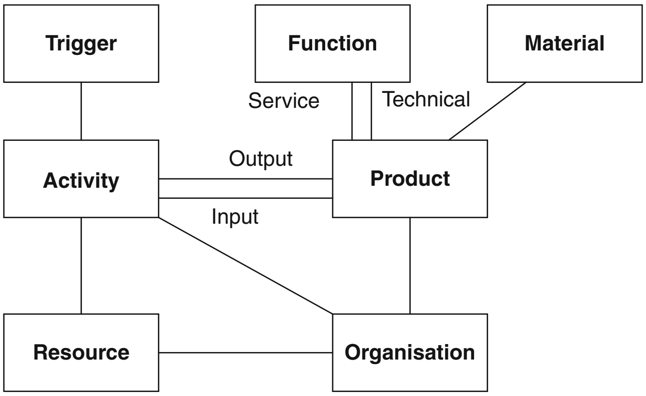

Fig. 5 Class diagram of the generic model

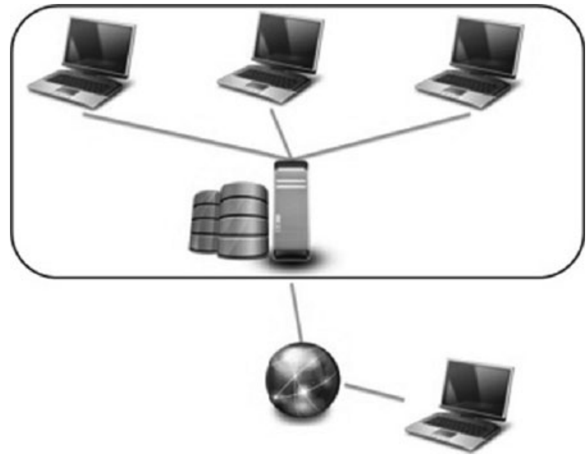

Fig. 7 Demonstrator's architecture

objects. The generic objects are represented in the UMLclass diagram (Fig. 5).

The different identified objects are the activity, the product, the material, the function, the resource, the trigger, the organization and the document. The activity specializes into task and operation, the organization into customer and supplier and the resource into material, human and software resource. More explanations about the generic model are in [14].

The objects at the generic level are not enough specific to be really useful in a particular company. A framework that proposes an instantiation of the generic model is proposed to match with the particular objects of each enterprise keeping a high level semantic alignment.

Based on modelling approaches like CIMOSA or GERAM [15, 16], the framework proposes a system with needs, processes and data model coherent for the three pilot enterprises. Figure 6 shows a cube representing the framework. The abscissa represents the three results of the modelling method: the needs map, the processes model and the data model. The ordinate represents the instantiation of the three components, the generic, partial or particular levels. And the depth represents the different views of the systems, process, information, resource and organization.

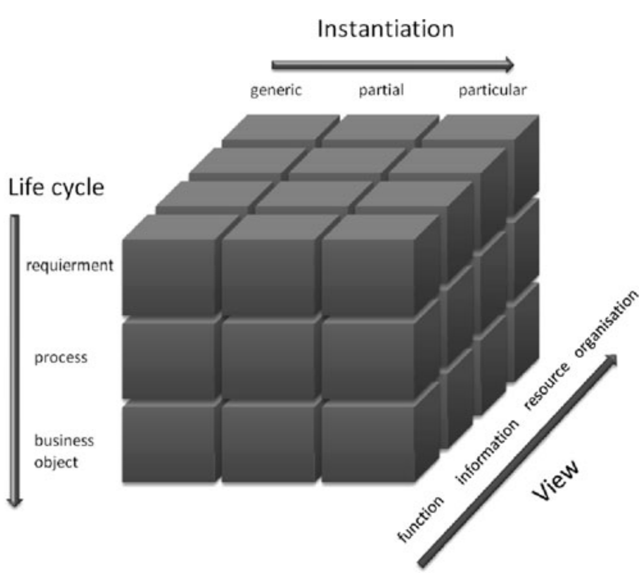

Fig. 6 Modelling framework

The generic model proposes a union of the process, information and resource views. It also integrates the organizational view that coordinates the other views. This axis notices the different views that are modelled, even if they are all integrated in the generic model.

A software demonstrator is created to automate the use of the framework in an industrial context. The architecture of the demonstrator is a rich client/ server one (Fig. 7). The client is developed in VB.Net and the server uses MS SQL Server. They communicate through SQL requests via http/https.

The proposed generic model is implemented in the demonstrator, with the generic classes, attributes and methods. Each class is specialisable in sub-class, inheriting of the attributes and methods of the father class. New attributes could be added to the new class. A new specialization is applicable to the sub-classes and so on.

The interface is constitued of a tool bar, a tree view, a fileview, a data card and a viewer (Fig. 8).

5 Application of the Demonstrator

The application is chosen to cover the maximum of identified needs. The study needs are: the configuration management, the link with the supplier, the multiple views, the link with the CAD and ERP, the routings management and the cost indicator.

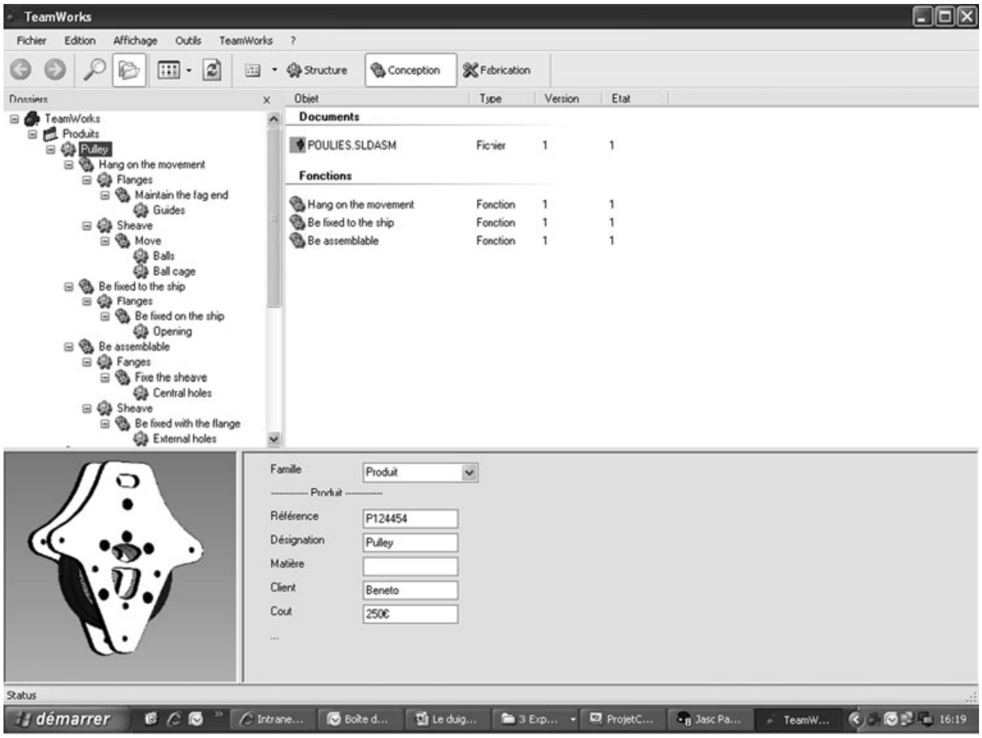

Fig. 8 Demonstrator's interface

The configuration management is partially covered by actual PLM systems. It is principally a request from the equipment manufacturer. The creation of product family and the differentiation between internal and external products is nevertheless simplified in the demonstrator.

To create a product family, the user right clicks on the generic class of product on the tree view and selects new. A new sub-class (a family of product) is created, inheriting of the attributes of the product class plus the new that the user defines for this family. Each product created in this family will obtain the attributes of the family. Sub family can be created reproducing the same method on a family.

The internal and external products are in the referential of the enterprise with different colours (yellow for the internal products and green for the external products). The external product can be taken directly from the supplier PLM systems. The different suppliers identified are present in a specific folder. A drag and drop from a component of the supplier to the demonstrator imports the product, all the attributes and the attached files.

The composition of a product is not the same depending of the user's work in the enterprise. There is no universal view appropriated for all the business units and each business view gives advantages to their users. In the present work, three views are retained: functional, structural and manufacturing [17].

In the structure view (Fig. 9), the components of the product are decomposed in the tree view. To obtain a functional view, the user has to change the view clicking on the function button. Then he can create functions under the product (the internal functions) and add in the components of the product (the functions of service of the components). So the product is decomposed from a functional point of view.

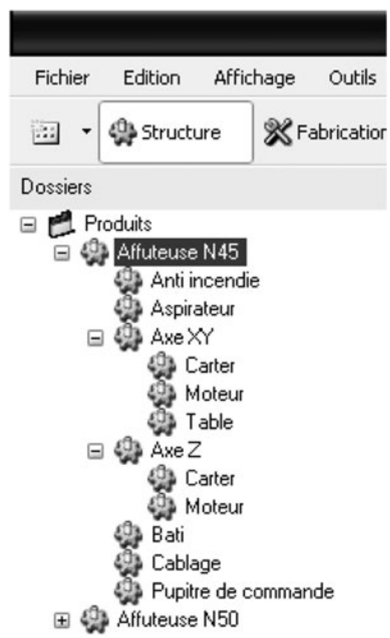

Fig. 9 Structural decomposition of a grinding machine

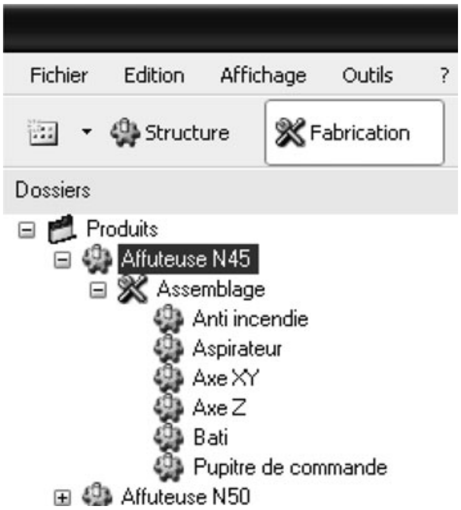

Fig. 10 Manufacturing decomposition of a grinding machine

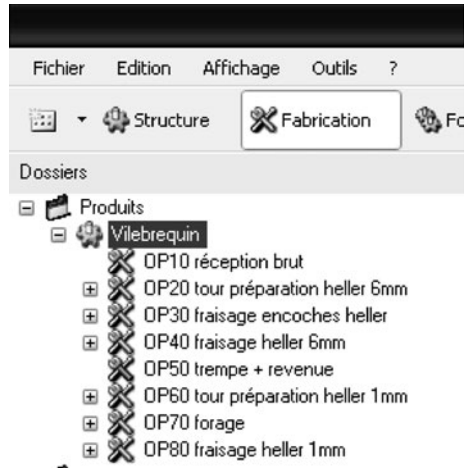

Fig. 11 Routing of a crankshaft

In the manufacturing view, the assembly operations are linked to the product and to the component (Fig. 10). This gives a manufacturing structure of the product through a product – assembly – component decomposition of the product.

In each view, some objects can be added separately. The object is visible in the selected view and not in the others. It could be the case for the addition of grease in the manufacturing BoM that do not have to be visible in the design BoM.

The interoperability of the PLM systems with the CAD and the ERP are the most important link to create [18].

For the CAD link, the designer imports the assembly tree view of the product with a drag and drop of the CAD file from the office to the demonstrator. The CAD tree view is then copied in the structure view. The components are created and the corresponding CAD files are imported in the right component objects. With the import of the CAD file, a link is created between the CAD attributes and the object attributes (for the attributes with the same name in the CAD system and in the demonstrator). Those attributes are then synchronized. The implementation is done on SolidWorks from Dassault Systems.

The manufacturing view can be synchronised with the ERP of the enterprise to obtain BoM and routings up to date. A mapping with an ERP is implemented in the demonstrator. It synchronised the items, the operations, the work centres, and all their respective attributes, updating the BoM and the routings. This is done on the ERP EFACS from EXEL Computer System, using the data base Informix from IBM.

The management of the routings directly in the PLM systems is a wish of the components and raw parts manufacturers.

To create a routing, the user creates the different operations in the product (Fig. 11). He can define optional operations, alternative operations and external operations (appearing in green and not in yellow as the internal operations). Then he loads the resources useful to each operation dropping the input items, the work centres, the tools. . .

The indicator the most requests for aid design and industrialisation in SMEs is the cost of the product, including the cost of the manufacturing processes.

The cost concept is present in the demonstrator. To have an estimation of the cost of a product, the user must create the routing of its product. It includes the components, the work centres and all the other consumables. Then the cost of each operation, each work centres and each component of the lower level of his decomposition is filled. Then the demonstrator calculates the estimated cost of the product.

6 Discussion

The contribution of this work is in two parts: on one hand the identification of the needs of mechanical SMEs in terms of PLM, and on the other hand the resolution of those needs based on a generic data model.

The identification of the needs of mechanical SMEs is done based on three representative companies. The number of studied companies is few for a generalisation but we assume that the choice of the companies based on the typology explained in section 3, combined with the immersion in those companies gives a realistic view of the problems encountered by the mechanical SMEs on this subject.

The second point is the realisation of the processes based on the generic model and adapted to the particular company following a modelling framework. The demonstrator implements the objects of the generic model and its specialisation. The implementation of this demonstrator in a company on a major project will validate the robustness and the appropriateness of our approach.

7 Conclusion and Perspectives

The SMEs do not easily integrate the PLM systems. Their needs do not match to the actual PLM functionalities. Our approach classifies the needs of mechanical SMEs based on immersions in three representative companies. The processes responses to the needs are formalized and implemented in the enterprises to test the solutions. A generalisation of the cases studies leads to a data meta-model deducted from the processes. This is the core to be implemented in the PLM system. Finally a demonstrator illustrates the use of the PLM system to solve the identified needs, showing the technical feasibility and the applicability of our approach.

The next contribution will be a detailed explanation of the generic model and the modeling framework to allow its use by other companies.

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Product Design Methods for Global Product Development

A Holistic Approach for Sustainable Product Design

H.S. Abdalla and M.A. Ebeid

Abstract There is an international imperative to reduce energy consumption and its associated gas emissions. Such reduction can be achieved in the electrical/electronic consumer products sector through the development of sustainable products. However, there is lack of information, knowledge, and integrated design tools for producing such products that embrace real sustainable characteristics. This paper presents a framework that integrates the various aspects of sustainable product design. It incorporates a set of guidelines, methodologies and tools for enabling the development of sustainable products. The proposed integrated tools will help designers at the early stages of design to bring forward sustainable electrical and electronic products and bridge the gap between engineering and ecology.

Keywords Sustainable design · Product design · Innovation in design · Holistic approach · Integrated design tools

1 Introduction

Sustainability guarantees the continuous availability of resources for the wellbeing of man and society through preserving the environment and concurrently raising living standards. Carrying sustainability to future systems, products and services requires the availability of sustainability awareness starting from the design and development phases [1].

There are many topics, issues and concerns that have to be considerd throughout the design and development of sustainable products. Those issues and concerns have to be carefully examined at the outset in order to maximise sustainability. Some of these environmental, economical and social issues/challenges are:

- The Impact of climate change, resulting in changing weather patterns, rising sea level and flooding.
- How to preserve resources which is a key driver in the design of electrical/electronic products to reduce the use of materials.

A study by the Industry Council for Equipment Recycling (ICER) in 2005, estimates that 939,000 tonnes of domestic electrical/electronic equipment were discarded in the UK during 2003 [2]. The main component of waste electronic equipment as shown in Table 1 is large household appliances known as white goods, which make up to 69% of the total electrical/electronic waste equipment. The next largest component is consumer equipment which accounts for 13% of this category and covers home entertainment equipment in its broadest sense, including cameras and musical instruments.

By weight large household appliances make up over two-thirds of domestic electrical/electronic products waste. This category includes not only large white goods but also freestanding heaters, microwave ovens and air treatment equipment. However, over 70% by weight of arising waste in this category are washing machines, fridges/freezers and cookers.

The study estimated the number of fridges and freezers being disposed in the UK at 3 million units annually. These units contain gases such as chlorofluorocarbons (CFCs) and hydro-chlorofluorocarbons (HCFCs) used for the cooling and insulation. Both CFCs and HCFCs are greenhouse gases which when emitted into the atmosphere, contribute to climate change. The interaction of electronic goods production and the environment may be considered as threefold: energy consumption, pollution electronic products in use, and pollution by toxic materials in wasted products at end of life. An example of the influence of the electronics industry on the environment is printed-circuit board (PCB) manufacturing. It is estimated that use of lead/tin soldering

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Table 1 Waste of domestic WEEE (The waste of electrical and electronic equipment directive) [2]

Categories of domestic WEEE	Tonnage discarded ('000 tonnes)	(%)	Units discarded (millions)	(%)
Large household appliances	644	69	14	16
Small household appliances	80	8	30	31
IT/telecoms equipment	68	7	21	23
Consumer equipment	120	13	12	13
Tools	23	2	5	5
Toys, leisure & sports equip't	2			
Lighting	2	<1	9	10
Monitoring & control equip't	<1	<1	<1	<1
Total domestic WEEE	939	100	93	100

in PCB manufacturing is amongst the worst polluters. In the pre-mounting phase of production only 7% of the material (copper) is retained on the board while 93% is pilled-of chemically, presenting a toxic waste. The importance of this datum becomes clearer when considering that excluding home appliances about 40% of the electronic waste is made up of printed circuit boards [3].

We can conclude that minimisation of waste in this very important production phase should be the responsibility of designers of PCBs. Their key task becomes: minimisation of the area occupied by the circuit for a given electronic function.

Sustainable development tools in terms of software or systems available for designers lack the integration of environmental, economical and social/ethical perspectives, and focus instead upon environmental aspects. An integrated sustainable design tool will help inexperienced designers at the early stages of design to bring forward sustainable electrical/electronic products and bridge the gap between ecology and engineering.

Among the many methods for sustainable product development and design are those focused on considering the basic problems and concepts of ecological and environmental design of electronic products from life cycle and end of life management perspectives [3]. The information flow and decision making in product development organizations, yielding methods for improving environmental information processing and defining product environmental metrics has been discussed in a research conducted by [4].

Attempts were made in previous research in order to modify and enhance the product's original conception [5], and a taxonomy of the various categories of environmental aspects are developed and the options for incorporating these aspects in the planning of the early phases of product development were highlighted [6].

Methodologies for the development of ideal eco-products by unification of extreme product versions [7] and designing sustainable product/service systems would be of a great use for designers [8].

There are different tools that are applied in the early stages of product design including frameworks for the development of environmental superior products (ESPs) based on design for environment (DFE) tools integrated with computer aided design (CAD) software to support designers in creation of ESPs [9].

El-Ganzoury and Abdalla [10] proposed an intelligent environment for total product development to enable designers to bridge the gap between marketing and engineering from the early stages of product development through the downstream activities and production.

Design for the environment strategies can play a significant role in product innovation by providing new criteria for evaluating design, including choice of materials, production techniques, finishing technologies and packaging methods. Such strategies consider the entire product life cycle, and can stimulate partnerships with suppliers/distributors, open new market areas, and increase product quality. The scope of design for environment encompasses many disciplines, including environmental risk management, product safety, occupational health and safety, pollution prevention, ecology, resource conservation, accident prevention and waste management [11].

Conceptual design of sustainable products is where concept generation and development of the product takes place. This area is becoming one of the top priorities of an ongoing research where the customer is being involved to help designers in developing product concepts [12].

The research discussed above focused on improving the environmental performance of products rather than integrating the key three aspects of sustainability. The high level of interaction between the three aspects needs to be illustrated in the design process of sustainable products.

2 Guidlines Concepts for Sustainable Product Dvelopment

Although the environmental challenges are the main concerns for sustainable electrical/electronic product design, a more holistic approach is needed to address the environmental aspects (energy consumption and reducing use of materials), economic aspects (minimizing costs in use and product prices) and social aspects (aesthetic design, and user interface design).

To achieve the proposed holistic approach and identify design requirements for sustainable products an investigation of the following areas related to sustainable product development concepts, methods and tools has been carried out.

2.1 Aesthetics Design in Sustainable Development

With the development of society, consumer place increasingly varied demands on the appearance and utility of products. It can be argued that the aesthetics of product design remain distinct from progress in engineering aspects, since aesthetics relate to mental image of shapes and forms rather than to technological functions of a product.

Based on industrial design, fuzzy logic theory and aesthetics principles, Cai and He [13] discussed the idea of driving the design process by semantics. In the process shown in Fig. 1, customer's performance was recognised in terms of semantics words, fuzzy evaluation models were built some covering shape and colour and associated aesthetics rules to analyze the products appearance design style. This method has already been implemented in a machine tool software system called computer aided industrial design (CAID).

Zafarmand et al. [14] and Fujita and Akagi [15] argued that the aesthetic appeal of products should be sustained during the product life cycle since aesthetic durability is a significant factor for product sustainability. Identifying and avoiding boring forms is one effective way of designing aesthetically sustainable products.

The system developed can coexist with a mental model of the aesthetic design process and seamlessly feed shape design results to engineering design efforts by defining aesthetic features and using parametric geometry as constraints among the different conceptual disciplines. Adding aesthetic sustainable design concepts as constraints to the proposed system is of great benefit to developing aesthetically sustainable products. Aesthetic appeal and fashion design was seen as an effective marketing tool for sustainable products as they fulfil corresponding sensitivities of the customer giving the design a social dimension.

2.2 Functionality

A product's functionality is what decides its nature or type. A product must fulfil customer requirements most important of which are functions expected from the product. Although functionality is important, ease of use of the product is one of the main issues to be addressed by designers.

Functionality of the product can lead to new and creative products by combining functions in one product. An example of a fax, photocopier and scanner all-in-one product shows the contribution to the sustainable design of products by reducing the amount of material used from an environmental and economic perspective. It also minimises the energy consumption and reduces running cost and emissions of green house gases.

2.3 Material Selection

Material selection is divided into two phases, material quantity and material type. Material quantity is dedicated to conserving environmental resources where designers try to minimise the amount of materials used in manufacturing the product. This addresses environmental aspects by preserving environmental resources and economic aspects of the product in terms of reducing product cost. While material type is concerned with compliance of the product with the restriction of the hazardous substances directive (RoHS) and minimising the amount of toxic material used which ends in landfill at the end of the product's life.

2.4 Cost

Cost is a major issue to be taken into consideration in the sustainable product design process. Designers should

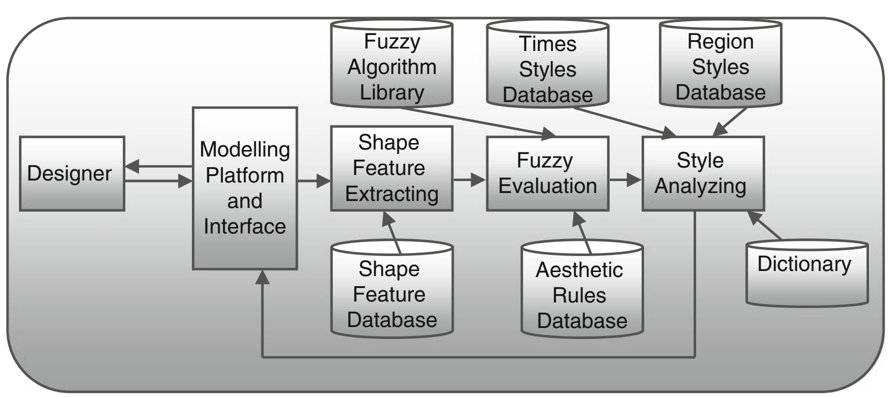


Fig. 1 Data flow of the CAID software [13]

not overlook the economic aspects in terms of costs of manufacturing, distribution and marketing.

3 Investigation of Electrical/Electronics Sector Needs

The results of a comprehensive survey targeting the electrical/electronics sector, showed that 88% of respondents felt that a comprehensive materials database would assist sustainable development, 84% needed to build an assessment system for green products, and 73% thought that a software assistant to act as an adviser was important in facilitating green design. All companies agreed that the issues of environmentally conscious products and waste management are key drivers for sustainable development.

The investigation illustrates the need for a comprehensive system to integrate all aspects of sustainable design. Of particular significance the73% of respondents who thought that a software assistant is needed. The paper presents a framework that integrates the various aspects of sustainable design.

4 Proposed Framework Architecture

The proposed framework attempts to consider most of the above aspects of sustainable design taking into account market and consumer requirements and including aesthetically sustainable design. The framework helps in developing the necessary concepts for designing a more sustainable design. Furthermore, the integrated system will enable users to design sustainable products from a holistic point of view.

The proposed framework incorporates several sustainable product design and development tools. The system will enable inexperienced designers to design sustainable electrical/electronic products by providing them with a set of tools to guide the user through the whole design process. It should also provide the relevant background and information required by the user to produce more sustainable products.

Integrating new electrical/electronic product concepts such as enhanced energy management techniques, and stimulating sustainable design concepts, are main aims of the proposed framework. In addition the framework is intended to enable designers to trace interactions between functions and environmental impacts and make necessary modifications to satisfy design requirements.

The proposed framework has three main layers with a user interface module at the heart as shown in Fig. 2:

- Design modules
- Design tools
- Design Databases

4.1 Design Modules

There are five main modules which reflect concurrent design processes. Each module corresponds to a particular stage in

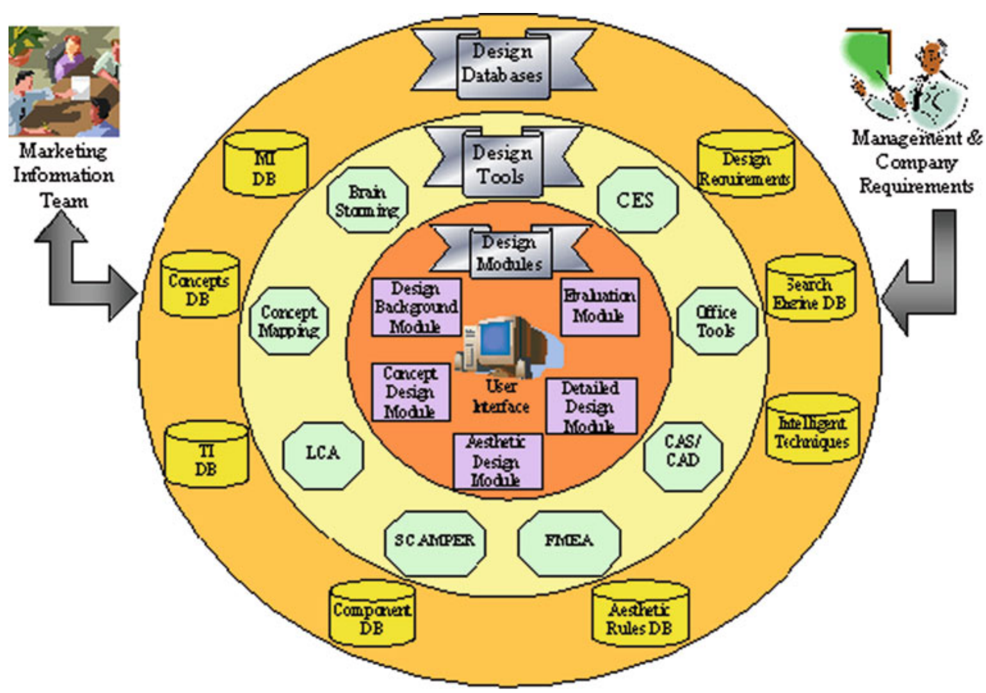


Fig. 2 Proposed system architecture

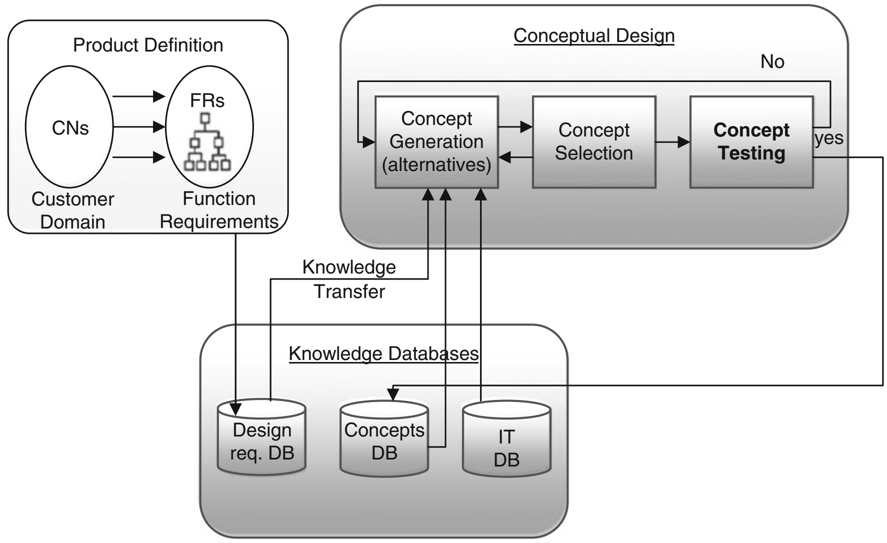


Fig. 3 Conceptual design sequence

the design process of the product. The process starts with the use of the design background module, followed by a concept design module, aesthetic design module, embodiment/detailed design module, and ends with the evaluation module. Each of the proposed modules is explained in the following sections:

4.1.1 Design Background Module

The design background module acts as an information supplier to the designer, providing all of the data needed to complete the design project. It introduces the product to be designed, or developed, in terms of its bill of materials (BOM), technical specifications, market and customer requirements. The designer is informed of the various design requirements including the Restriction of Hazardous Substances Directive (RoHS) requirements and the Waste Electrical and Electronic Equipment Directive (WEEE) requirements. The module also supplies the designer with background information about relevant sustainable design concepts, and methods to stimulate sustainable design thinking. The information is organised in a way that is easy for the designer/user to access.

4.1.2 Concept Design Module

The conceptual design phase of the framework is at the heart of developing sustainable electrical/electronic product based upon new sustainable concepts. At this stage various product alternatives and concepts are presented to the designer based upon product domain, category and functional requirements. The designer then selects a product concept (alternative) after comparison with other alternatives based on the specified design requirements. Figure 3 shows the conceptual design sequence for generating product concepts (alternatives).

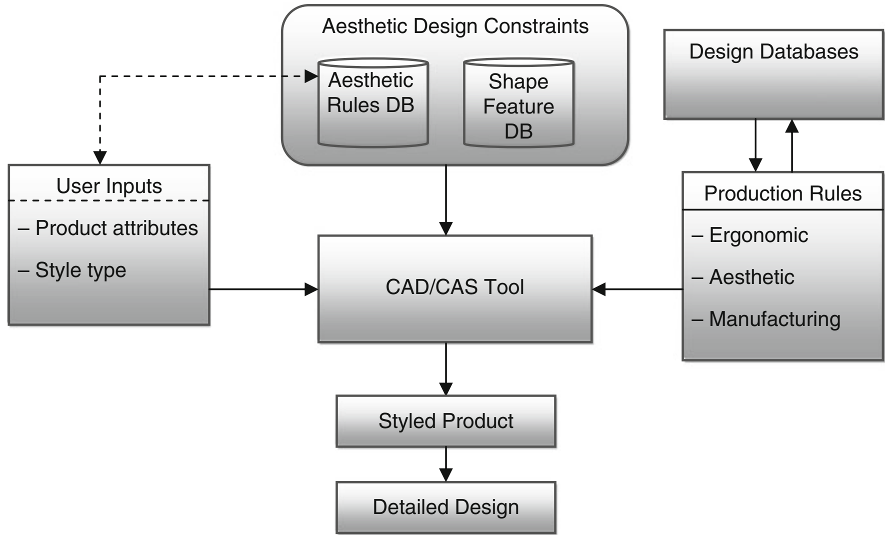
4.1.3 Aesthetic Design Module

The design of a sustainable product has to be aesthetically durable. The purpose of this module is to guide the designer through a computer aided design (CAD) tool to develop an aesthetically sustainable product by introducing rules and constraints for aesthetic sustainability as shown in Fig. 4. The module also helps the designer to minimise the use of materials through a shape feature database containing shapes of different aesthetically sustainable designs.

4.1.4 Detailed Design Module

The detailed design module is where functional decomposition of the product takes place to allow mapping of each function to the relevant components for that function to be achieved. The system uses a hierarchical approach which is the function analysis system technique (FAST) to define, analyse and understand product functions. It also considers how the functions relate to one another and which functions requires attention to increase the product's sustainability. The module also helps the designer to select appropriate materials through a material declaration tool integrated within the system to ensure compliance with the RoHS and the WEEE directives. Figure 5 shows the detailed design window of the system. In this example the product function tree has been generated for a coffee machine following the selection of the product alternative. With the design specifications and requirements available the designer can select the appropriate functional components and materials for developing the product.

Fig. 4 Aesthetic design stage



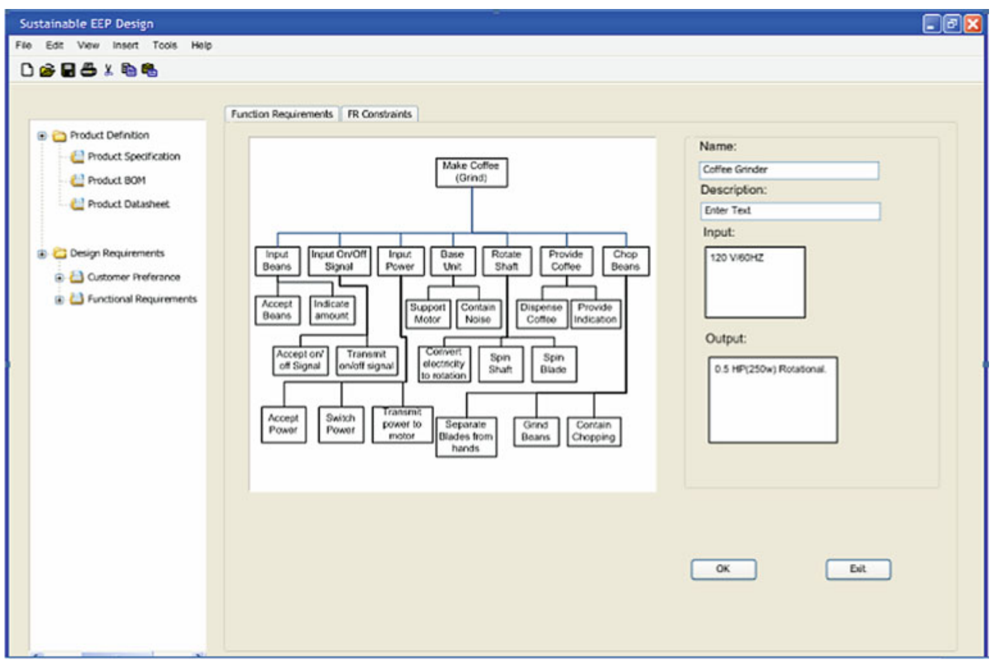


Fig. 5 Detailed design window

4.2 Design Tools

The main purpose of the system is to provide the user with a set of concepts and tools to help in designing sustainable electrical/electronic products. These tools therefore, comprise a major part of the developed system, as described below:

- *Brainstorming:* This is a problem solving technique for generating, refining and developing ideas by creating a list that includes a wide variety of alternatives. There are several techniques for conducting brainstorming graphically, verbally or by using a software tool. In this research a mind mapping tool for brainstorming is suggested where the designer uses this tool to identify solutions for existing design problems and design concepts. The technique can also be applied by a design team through a discussion session where all ideas are welcomed for refinement combination and enhancement.
- *Concept Mapping:* This is a very useful tool in design concept generation as discussed in previous research projects. The idea is derived from brainstorming as it stimulates generation of new and innovative ideas as well as refining them. A concept map can provide an intuitive assistive cognitive medium for comprehension of the various data types encountered in product development.

- *Life Cycle Analysis/Assessment (LCA):* this is a tool that analyses the different phases of the product life (production, use, disposal) and pinpoints for designers the phases of the product life cycle that need refinement. The tool is used in the proposed system to calculate environmental impacts of the product, such as energy consumption and material production impacts.
- *SCAMPER:* SCAMPER is an acronym for (substitute, combine, adapt, magnify or minify, eliminate or elaborate and rearrange or reverse). These headings make up a checklist for stimulating ideas of possible product modification. SCAMPER helps the designer to think about different ways that an existing product could be modified and is a very useful tool for concept generation and the development phase of design.
- *FMEA:* FMEA is an acronym for (Failure Modes and Effects Analysis). It is a very useful tool for systematically appraising the potential failures of a product, and for ranking their importance by considering separately the modes of product failure and their potential effects on the customer. The output from FMEA should be seen as a prioritised menu for changes to be implemented during subsequent stages of the product development process. FMEA is used in the system as an evaluation tool for design.
- *CAD/CAS Tools:* Computer aided design and computer aided styling tools has been integrated within the system to help designers achieve the aesthetics of the product, and to provide designers with flexible sketching media.
- *Office Tools:* Office applications such as spreadsheets and word processing can be integrated with the system to assist in adding comments and making comparisons.
- *CES Selector:* Cambridge engineering selector is a software database system for computer-assisted selection of materials, manufacturing processes, structural sections, and other variables in engineering design. The Cambridge Engineering Selector (CES^{TM}) helps engineers find optimal material/process/shape combinations, which maximise performance, and minimise cost. The CES^{TM} Database contains a set of seven data tables (materials, manufacturing processes, structural sections, suppliers, references, uses and industrial sectors). These tables contain unique, high quality, validated data linked together in a versatile relational structure.

4.3 Design Databases

The design databases store and give access to the different information needed by the user at the different stages of the design process. Some of the system databases will be updatable by the user. Others will be fixed and act as read-only databases.

The proposed databases for the system are:

- *Marketing Information Database (MIDB):* The MIDB contains necessary data about the similar products available on market in terms of product name, cost, abstract and description. This information provides the user with a background about other competitive products, and the market share of each product. The data for this database is provided by the marketing team and provides an overview of the market status.
- *Concepts Database (CDB):* The CDB stores various concepts of sustainable design for the user to explore and to add new concepts developed by the design team. The database will also be linked to the concept design module for newly inclusion of generated and developed concepts.
- *Technical Information Database (TIDB):* The TIDB contains technical information providing the user with the latest about state of the art technologies and functions that might be needed.
- *Components Database (CDB):* The CDB database contains a set of electrical and electronic components that the user needs in designing the different electrical/electronic circuits in the product. It is linked to the circuit design CAD tool and the materials database in order to facilitate choice of materials for designed components.
- *Aesthetic Rules Database (ARDB):* The ARDB contains the rules used for designing the aesthetics of the product. These rules cover principles of shape such as stability, legerity, symmetry, balance, rhythm and cadence, and principles of colours such as contrast, harmony, stability and legerity.
- *Intelligent Techniques Database (ITDB):* The ITDB data base will provide the user with the latest techniques and technologies available, such as traceability and energy saving techniques in order to design sustainable electrical/electronic products.
- *Design Requirements (DRDB):* This database will contain the market and customer requirements, time limits, budget and cultural influences on the design. The user can refer back to this database at any point in the design process. The DRDB will be built by designers based on market research and meetings with clients.
- *Search Engine Database (SEDB):* The SEDB connects the user with internet sources to conduct searches in different fields. Results will be held in this database until the design process ends when relevant information is added to other relevant databases in the system.

5 System Scenario

The scenario of the proposed system is illustrated in Fig. 6 and can be summarised as:

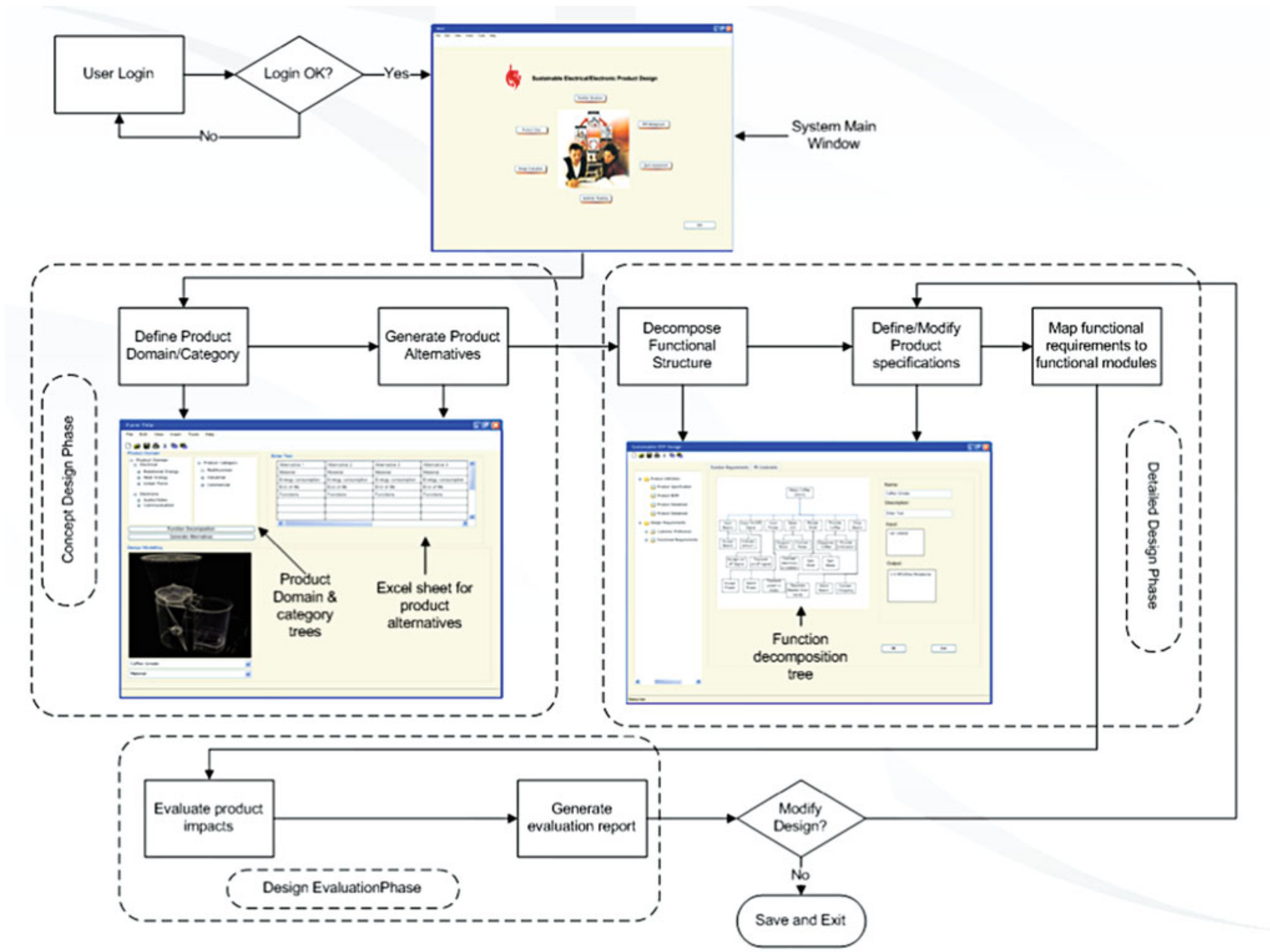


Fig. 6 Proposed system scenario

- Step 1: The user logs on to the system providing a unique user name and password.
- Step 2: The main window of the system opens for the user and provides six options for the designer to choose from.
- Step 3: The user navigates through the product domain and product category tree for the system to provide design alternatives and a 3D model.
- Step 4: The concept design module searches the concepts database for a product that satisfies both the product domain and the product category.
- Step 5: The results of the search are then considered as potential design solutions.
- Step 6: At this point the designer is able to modify the available 3D model.
- Step 7: The system performs a functional structure decomposition of the chosen design alternative to allow mapping of each function to the functional component that satisfies it.
- Step 8: The user defines the product specification for the system to select the appropriate component according to relevant specifications.
- Step 9: The user makes selective use of the provided tools to evaluate the product impacts, and to ensure compliance with legislation.
- Step 10: The system generates an evaluation report for the designer with advice on aspects for improvement.

5.1 Energy Consumption Calculations

The system also provides the user with a quick assessment tool to determine the environmental impacts of a certain product. The product life cycle scenario is fed into the system, e.g. number of working hours per day, amount of energy used in on-mode and standby mode, as shown in Fig. 7. The system is then able to generate a report of the total

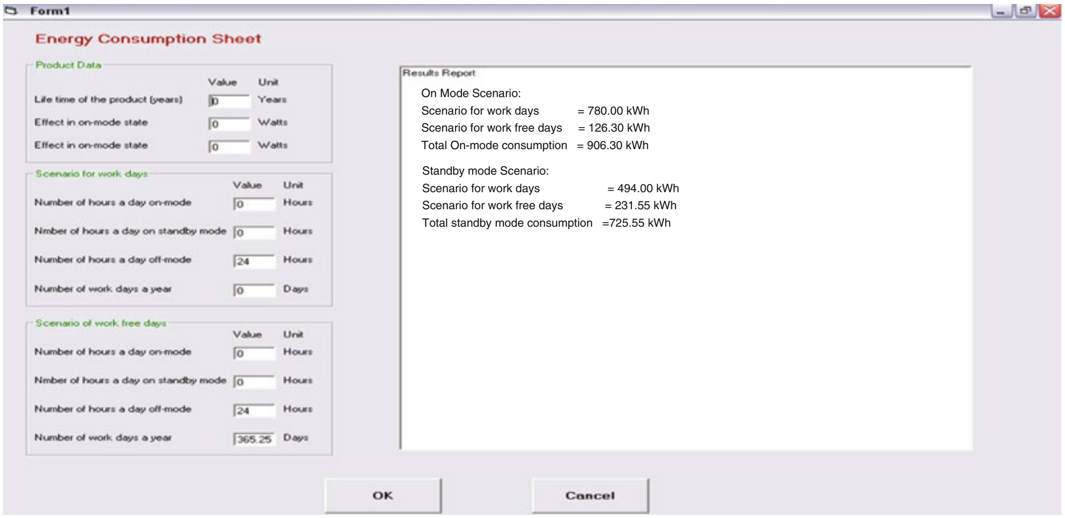


Fig. 7 Energy calculation sheet

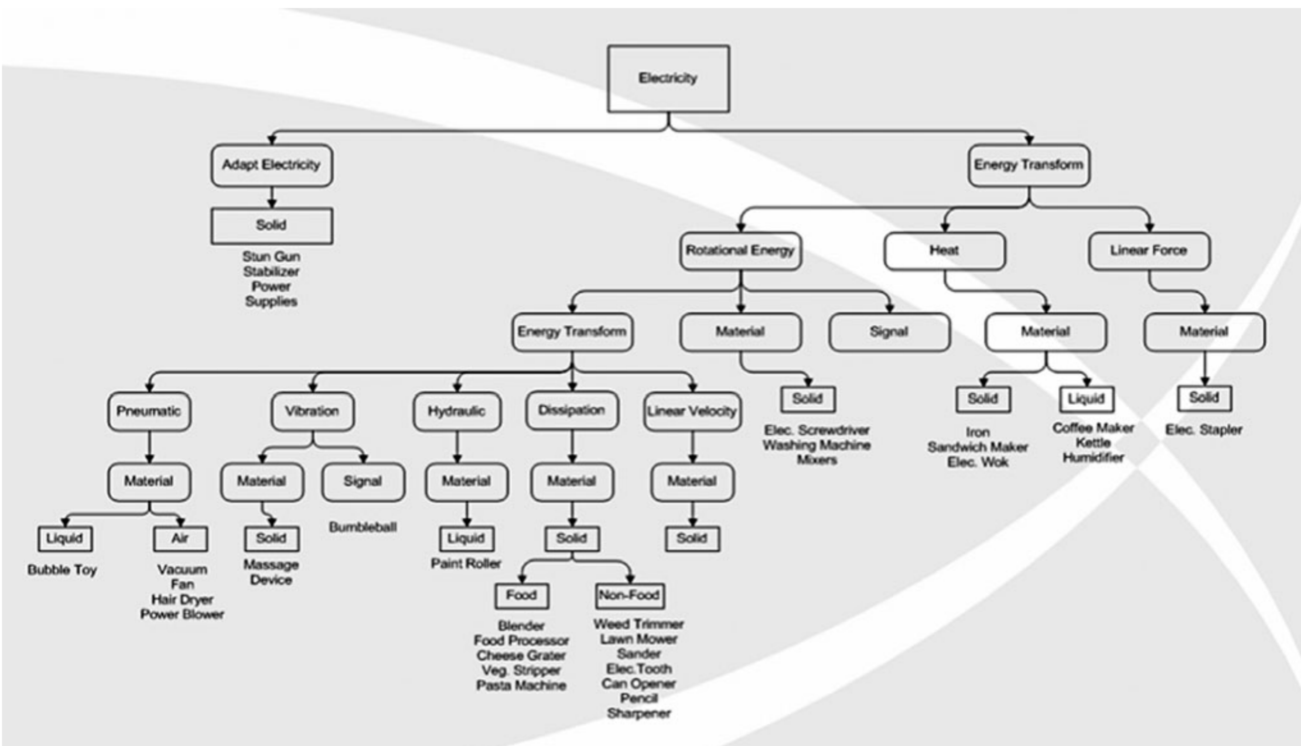


Fig. 8 Product hierarchy for product with electricity as primary input flow

environmental impact of the product with a material declaration report about the amount and type of material used.

5.2 Functional Decomposition

The proposed system uses a product hierarchy with electricity as a primary input flow, as illustrated in Fig. 8. This is a functional decomposition hierarchy for identifying the product domain according to the functions they are able to achieve.

5.3 Software Considerations

The proposed sustainable electrical/electronic product design system is coded and implemented on Visual Basic V6.00. A CAD solid modelling system is integrated for design representation. The knowledge representation, material declaration and power consumption calculation was provided by Excel sheets.

6 Conclusions

The proposed system presents a novel and holistic approach that integrates the three pillars of sustainability (environmental, economical and social aspects) in a user-friendly interface. Some of the main charasteristics of the system are to:

- Guide designers towards developing more sustainable electrical/electronics products.
- Stimulate the Integration of new concepts into the product design and development processes.
- Enable users to trace interaction between functions and environmental impacts.

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Method-Supported Product Development for Post-series Supply

U. Dombrowski, S. Weckenborg, and S. Schulze

Abstract The increased use of innovative components like electronics is a present trend in several branches of industry. These components are characterized by short innovation cycles, but are often assembled in primary products, which have a comparatively long life span. The post-series supply is therefore a relevant problem. Today the focus of product development lies on small expenses in the serial production, a consideration of life cycle costs with regard to the post-series supply does not take place. This behavior often results in high financial burden. Before this background the product development with consideration of the requirements of the post-series-supply offers high potentials. To reduce the complexity of this problem a methodical approach is needed.

Keywords Spare parts management · Product life cycle · Product development

1 Introduction

In a competitive environment the customer satisfaction is a critical factor for the success of an enterprise. Not just the right design and functionality of the product, but in an increasing degree the service to the customer decides on his satisfaction with a bought product and whether or not he will buy products from this brand again next time. One important factor for the service in connection with long-living primary products like automobiles is the availability of spare parts also far after the end of production (EOP). For example in the automobile industry supply periods take at least up to 15 years, in the upper class even longer. Other branches, like the aircraft or the printing industry, have an even longer service period of 30 years.

For the wear parts a prognosis of the demand is relatively trivial. In the product development process they have been designed for a defined period of time or performance. E.g. in the enterprise exists plenty of knowledge, experience and historical data for a coupling disk to make a quite exact forecast of the demand in the next years. In contrast the considerations of spares, which are designed for the whole lifetime of the primary product, like electronic components, are way more difficult. Since there are no historic data for these innovative products, failure causes for these spares are not well-known. By ways of a failure mode and effect analysis some possible failures may be detected, but the prognosis of the demand are afflicted with large uncertainty [1]. Unfortunately the dimension of this problem is getting bigger. The average value share of electronic components has risen in the average by 6.4% each year since 1995. The value of electronics in an automobile will rise up to 30% until 2015. One reason for this trend is that most innovations in the automobile sector are realized by electronics [2]. The supply after the end of the series production is therefore a substantial problem in the automobile industry.

As to be seen in Fig. 1, the life cycle of a vehicle is substantially longer than the life cycle of the employed electronic components. In the example shown the automobile has a life cycle of 24 years, starting with the development, the serial production and ending with the usage. The average age of automobiles has risen considerably in the past. E.g. in the last 37 years the average age of the vehicles in Germany rose from around 3.7 to 8.1 years [3]. In most countries of Western Europe or North America a similar trend can be identified. In contrast to the long product life of the automobile the electronic components are designed for the consumer electronics and IT markets, in which the customers demand short life cycles and innovative products. Although the amount of electronics increased in the last decades, the power of the automotive industry in the semiconductor market is too small to enforce an extension of the production time of electronic components. It becomes clear that the problem of the component discontinuation notice can arise early in the life time of the primary product, even within the range of the

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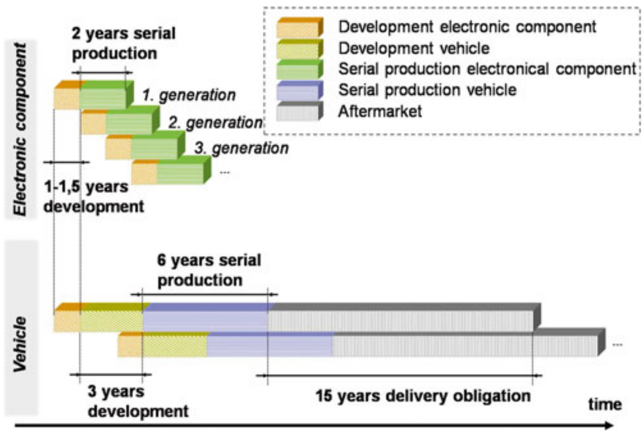

Fig. 1 Life cycles of vehicles and electronic components

development, and be expected to become urgent within the aftermarket. The long-term availability of the components is therefore not given and can lead to a risky final stockpiling or an expensive redesign [4].

2 Supply Strategies and Scenarios

Short term planning and measures for the post-series supply will result only in suboptimal solutions. Because of the long time horizon and the high financial risk long-term planning is necessary. Therefore the model of the life-cycle-oriented spare parts management was conceived [5, 6]. It contains six supply strategies for an efficient post series supply, which may be combined to supply scenarios. The six strategies to guarantee a lifecycle provision of spare parts will be characterized shortly at this point:

- Compatible successive product generations,
- storing of a final lot,
- periodical internal production,
- periodical external production,
- reuse of used components and
- repair of used components.

1. Compatible successive product generations: During product development of the next product generation the downward compatibility has to be maintained. So the next product generation can be used as spare parts for defective components of the previous product generation. The successive product generation may have additional functions, but the restriction of compatibility will restrain revolutionary technological development. The installation space, the fixing and the interfaces need to be the same. One possibility to deal with these disadvantages is the differentiation by software.
2. Storing of a final lot: Either at the EOP or when the periodical production is not economically anymore, a final lot is manufactured based on an estimation of the lifecycle demand. A reboot of the production at a later date is not intended; production and testing equipment will be sold, used at another production facility or disposed. The estimation of the final lot is a demanding task, because a later revision is not possible and a failure can be very expensive. Normally there will be either an overstocking, i.e. after the supply period surplus components have to be scraped, or there is an underestimation of the demand. In the latter case the production has to be re-established or a redesign of the component has to be done. In the automobile industry the redesign of an electronic component will cost depending on the complexity between one and eleven million Euro [7]. Furthermore the function or the process ability after storage of electronic components is often not guaranteed by the producer.
3. Periodical internal production: After the EOP spare parts will be manufactured in small or medium-sized lots on the machines, which have been originally used for the serial production. Because of the small lot sizes higher set-up and maintenance costs of the facilities will increase the costs per unit. In addition to this the production facilities, specific tools and test equipment for the spare parts need a lot of space and knowledge about the manufacturing processes is necessary. Furthermore, the supply of electronic parts for the production of the components must be assured over a long period of time. Product discontinuations of electronic components endanger the supply during the post-production-phase and will force to find either equivalent assembly parts or to change the supply strategy [5, 6].
4. Periodical external production: The Original Equipment Suppliers (OES) have their core competence in the serial production of large lot sizes and in predictable quantities. After the EOP the conditions for manufacturing change immensely and an outsourcing of the production to a specialized electronic manufacturer can be an adequate solution. Another possibility is to establish a spare parts factory, which is owned by the OES but will work independently.
5. Reuse: Still working electronic components from inoperable vehicles can be reused as spare parts after their reliability was thoroughly checked. In order to get enough of the used components back to the OES the establishment of a reverse logistics system is essential, which is embedding the service stations. Thoroughly checking of the reused components is necessary to guarantee that only faultless components will be delivered to the customers. However, for vital functions, such as an airbag controller, this strategy is often not suitable [8].
6. Repair: As seen by the strategy reuse a reverse logistics system has to be established. But not just working components will be collected; also defect components will be collected, inspected and repaired. The reconditioning

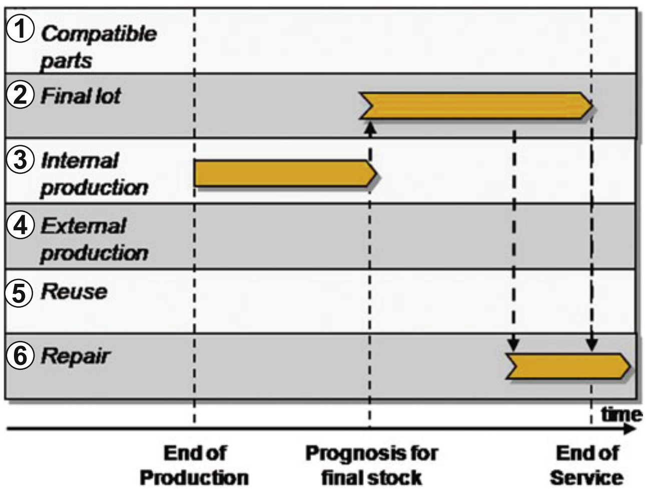

Fig. 2 Supply strategies and scenarios

of electronic components depends on some premises, but is a well suited strategy to guarantee a long-term service without the need of an early stockpiling. This strategy is characterized by does not need highly accurate forecasts and the flexibility to react to unsteady demand is much higher than with other supply strategies [9].

Each strategy has specific advantages and disadvantages. Because of the specifics of each component a general decision for one strategy is not reasonable. Often it does not make sense to pursue one single supply strategy over the entire supply period due to the changing conditions like decreasing demand. Different strategies may be combined to a supply scenario, with which the supply can be guaranteed until the End of Service (EOS) within optimal costs at low risk. An exemplary scenario is shown in Fig. 2. After the EOP the periodical internal production of the electronic components is continued. Due to the decreasing lot sizes this strategy can be accomplished economically only up to a defined point in time. If a secured forecast can be provided, a final lot can be manufactured. In this scenario the repair of used components is a possibility to catch any shortages in case that the demand prognosis was faulty [5].

3 Life Cycle Orientation in Actual Planning Processes for Spare Part Management for Post-series Supply

3.1 Actual Planning Process

In current approaches of planning and controlling for the post-series supply the first step is the identification of basic characteristics of the considered component (Fig. 3). These

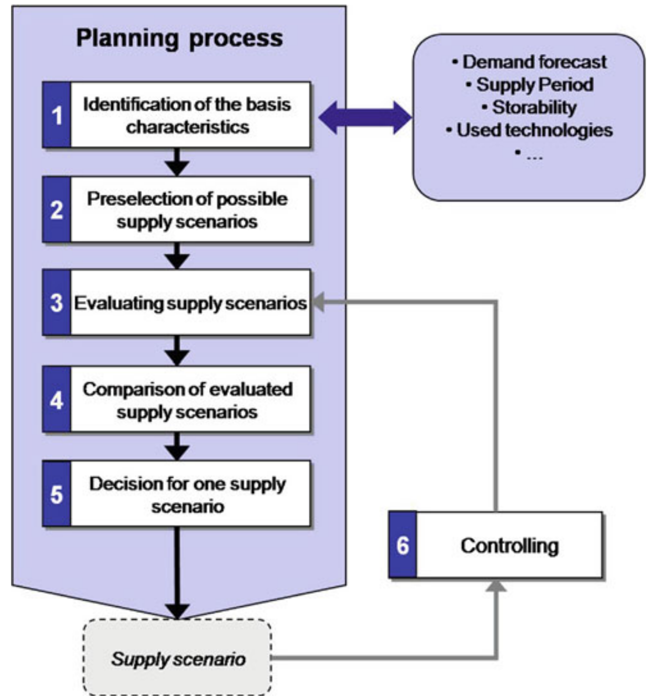

Fig. 3 Planning process for a life cycle oriented spare part management

characteristics are for example the demand forecast, the plausibility, i.e. the risk of the forecast, the length of the supply period, the storability of the component and the manufacturing technologies. Based on these basic characteristics, the pre-selection of possible supply scenarios is done in step two. Afterwards, in step three, an evaluation of the different supply scenarios takes place and in step four the comparison of the evaluated scenarios. Step five contains the decision for an adequate scenario. During the supply period the decision must be continuously controlled and eventually starting again from step three a change in the supply scenario has to be considered [4, 10].

It is obvious that current approaches of planning and controlling of the post-series supply are just reactive and based on decisions made in the past. I.e. planning begins at the end of the serial production and thus has the disadvantage that a supply scenario will be determined on the basis of existing product characteristics. E.g. the selection of a supply scenario for a control unit for an automobile will be based on the components and the manufacturing processes of this control unit. Due to this characteristic some economical supply strategies are excluded from the further decision process. If the control unit cannot be opened without destruction because of a sealing against humidity, the strategy repair has to be excluded. An early consideration of the post-series supply in the product development could have had a positive influence on the product life cycle costs [11].

A target-oriented development regarding the post-series supply is momentarily not supported by the planning process [5]. In order to abandon the reactive planning and to reach higher degrees of freedom during the selection of a supply scenario a new planning method has to be established.

3.2 Evaluation of Design Approaches

Despite the inherent potential the industrial application of product development with focus on the post-series supply is relatively low. Approaches of some Design for X methodologies can be taken. E.g. the Design for Environment (DFE) considers aspects that are also relevant for the post-series supply. It includes requirements as legal regulations such as the European Community directive for the recovery of end-of-life vehicles and the European Community directive on waste electrical and electronic equipment (WEEE), requiring the vendor to the redemption of their products. The recyclability of the products is often accompanied by possibilities for an easy repair [12–15]. Design for Service aims at extending the use phase of a product and at lowering the product life cycle costs. The easy detection of failures and the installation of components are goals of DFS and benefit the reuse or repair of electronic components [16, 17]. Individual technical guidelines give design suggestions, such as the VDI guideline 2246 for Design for Service. The possibility for an easy installation and removal, the interchangeability, the testability and the standardization as influencing parameters are identified as significant parameters influencing the reparability of a component [18]. These properties do not aim specifically for the reparability of innovative components, but can be transferred to this problem area. But there are lacking approaches to assess a product with regard to the identified parameters.

Product development approaches, such as the cooperative product engineering and the simultaneous engineering (SE) or the VDI guideline 2221, systematize the phases of product development, but they describe the problem in a universal form for all industries [19–21]. The objectives to structure the product development process (VDI 2221), to shorten it by overlapping of the individual phases (SE) or to rise the quality of the product development by the multidisciplinary composition of development teams, have also validity in the product development of electronic components. However, in these approaches the main problems arising from the short innovation cycles are not addressed. Due to the complexity of the considered problem and to the numerous parameters on the selection of an adequate post-series supply scenario the problem cannot be solved by the general approaches described.

The consideration of requirements of the post-series supply already in the product development has not been systematically investigated yet. Therefore, a methodology to develop a component for a defined post-series supply scenario is lacking. Such a methodology could realize significant cost savings in the post-series supply and therefore reduce product lifecycle costs. In the next chapter the derivation of a methodology for a design according to the requirements of the post-series supply is described.

4 Method for Product Development Regarding Post-series Supply

It is not possible to reach all optimal parameter values of a post series supply in one product. The optimization should be focused on a strategy or a scenario to keep a limited number of requirements for the product. In this chapter a method in four steps is described (Fig. 4).

In order to determine the relevant requirements for the post-series supply, in the first step the requirements of the supply strategies have to be identified. In the second step an adequate supply scenario of the component has to be determined. This supply scenario has to be based only on the basis conditions like demand and supply period to guarantee the independency from technical component characteristics. In the third step the characteristics of electronic parts and manufacturing processes have to be characterized with regard to the requirements of the supply strategies. In the fourth step the data are combined and the most important requirements for product development are determined. Alternatively a guideline with general requirements could be established. However, the high number of requirements would be a disadvantage, so that the acceptance in product development is not given anymore.

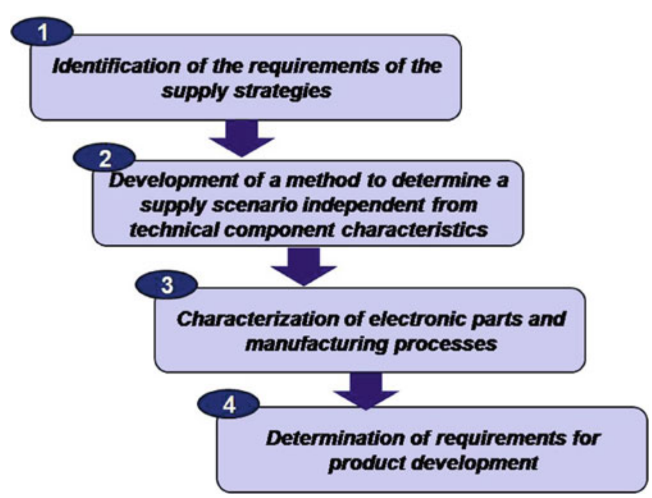

Fig. 4 Four steps to generate the requirements for product development

4.1 Identification of the Requirements of the Supply Strategies

In a first step requirements, which have relevance to the post series supply, must be identified. Furthermore, the individual requirements must be assessed objectively and traceably for each supply strategy. E.g. one requirement is the housing closure of a control unit. A possible specification could be the possibility to open it without demolition of the component or not. For the strategy repair it is necessary to open the housings, for the other strategies it is of no relevance and therefore it does not need to be considered. If, later on, the strategy repair is identified as a reasonable strategy for the component, the product development should consider screw connection or snap connection instead of a glued housing. Figure 5 shows the matrix, which contains the strategies and the requirements.

Different post-series supply strategies are evaluated regarding to the relevance of the identified requirements. The evaluation differentiates between "necessary" and "preferable". Necessary requirements need to be fulfilled; otherwise the strategy cannot be accomplished. Preferable requirements may help to implement the strategy or will generate an advantage in consideration of cost or service. As seen in Fig. 5 the long-time storability of an electronic component is necessary for a final lot, because the components will be stored for the rest of the supply period. For the internal production e.g. it is just preferable because lot sizes can be more flexible, when the components have no expiration date.

The deduction of the requirements is done in close cooperation with an automobile supplier. Even though a thoroughly literature analysis is done to collect requirements also from other industry branches.

Supply strategy \ Requirements	Open closure without demolition	Storability component	Storability parts	Long-time availability of parts	...
1 Compatible Parts					
2 Final Lot		✚			
3 Internal Production		●	✚	✚	
4 External Production		●	✚	✚	
5 Reuse		●			
6 Repair	✚	●	●	✚	

✚ Necessary
● Preferable

Fig. 5 Evaluation of the requirements of the supply strategies

4.2 Development of a Method to Determine a Supply Scenario Independent from Technical Component Characteristics

The goal of the second step is to develop a method to determine a supply scenario independent from technical characteristics of the component. The actual planning methods select a supply scenario depending on product characteristics which are already fixed (see Chap. 3). Due to the fact, that the decision for a scenario should be reached before product development, a new method has to be established.

The main criteria for the selection are the costs and the risk of the scenarios. The input variables for the decision process are for example the expected demand, the aspired duration of the supply period, the expected return volumes, corresponding delivery obligations, the need for continuity, etc. Existing forecasting methods have to be analyzed and combined to a method which considers the relevant factors. Further on not just the overall demand is of relevance; also the distribution of the demand over the supply period is important. Is the demand quite constant or will it decline exponentially? During the decision process a decision about the allowed risk has to be made. In every scenario exist risks, but their dimension is differing. Depending on the enterprise the maximal allowed risk has to be determined.

The selected supply scenario is the input parameter for the product development and has to be discussed between the product development and the manufacturing before starting the development process [22]. In the product development the defined requirements of the selected scenario have to be considered to realize the supply scenario in the supply period.

4.3 Characterization of Electronic Parts and Manufacturing Processes

After analyzing the requirements of the supply strategies and determining a supply scenario with the lowest cost and an adequate risk in the third step the electronic parts and the manufacturing processes are described systematically. This establishes the possibility to assess the suitability of electronic parts and manufacturing processes according to the supply strategies and scenarios and supports an appropriate selection of parts and processes according to the selected scenario. Currently this assessment is not part of the product development of the post-series supply, because the requirements from the product life cycle, for example the usage of components which have a short storage capacity, are not known.

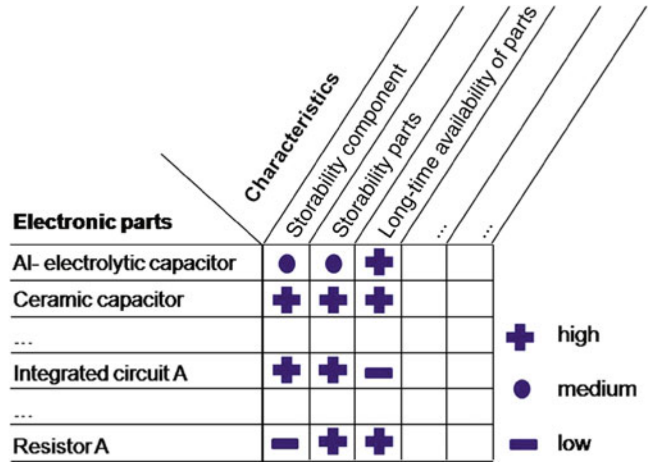

Fig. 6 Characterization of electronic parts

For example the storability of electronic parts with regard to their function and their processability, the storability of complete components and the estimated availability of parts in the future are characteristics for parts, which have an influence on their appropriateness for a selected strategy (see Fig. 6). Based on their characteristics the electronic parts are clustered. For example, an electronic part will function after a long storage but can be problematic in the subsequent processing because of corroded contacts. This would mean higher storage cost of this part because e.g. a dry-pack or nitrogen cover gas has to be used. With the clusters the selection of appropriate electronic parts during product development will be easy and user-friendly.

Examples of the relevant characteristics of manufacturing processes are the standardization of the process and the production quantity. Processes that are standardized and therefore often used in the enterprise are easier to accomplish in the post-series supply than specialized processes for a

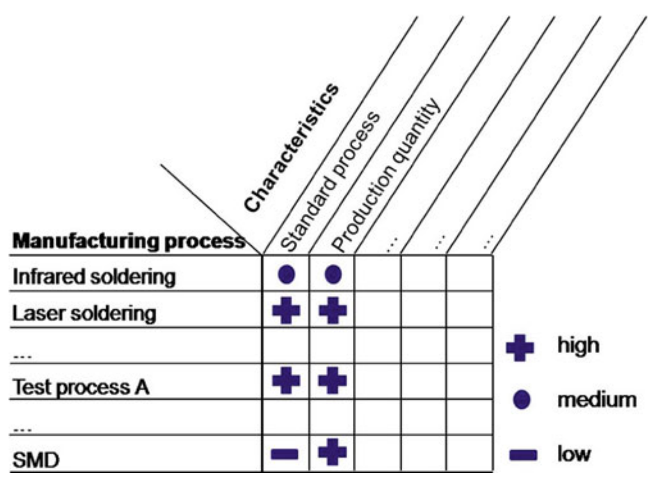

Fig. 7 Characterization of manufacturing processes

component, that maybe economical during serial production but will produce high costs afterwards. On this categories the manufacturing processes can be classified and allow the selection of the appropriate manufacturing processes with regard to the supply scenario (see Fig. 7).

4.4 Determination of Requirements for Product Development

The results of the previous steps are combined in the fourth step and determine the most relevant requirements for the product development. The starting point is the selected post-series supply scenario based on the derived method from step 2, whereupon the relevant requirements of the supply strategies can be derived, as they were identified in step 1. The relevant requirements will lead directly to the most convenient categories of electronic parts and manufacturing processes. Product development may use the proposed parts and processes to generate a product that will meet the requirements of the selected strategy. The costs in the supply period can decline significantly in the aftermarket. Further on the risk of not being available to deliver can be decreased. The method enables the engineer during product development to create in short time a product that has a high compliance with the requirements of the post-series supply.

5 Summary

Due to the increased use of highly innovative components like electronics and the different innovation cycles between these components and the primary products it is necessary to establish an effective spare parts management. Today the supply scenario is determined at the end of serial production and is therefore a reactive measure without much degree of freedom. Through early consideration of the requirements of the post-series supply in the product development the product life cycle costs could be decreased considerably.

In this chapter an approach for a method to determine the requirements of post-series supply was derived. In a first step the requirements of the supply strategies like storability and long-time availability of electronic parts were identified. Afterwards the determination of an adequate supply scenario of a component has to be determined without regard to technical characteristics. Just basic conditions like demand and supply period are considered.

Afterwards electronic parts and processes are evaluated concerning the requirements of the supply strategy. Which electronic parts can be stored? Which processes can be done on standard machines? Combining the results of these three steps, the requirements for the product development can be defined. Due to the limited number of requirements it is much easier to deal with them as if a general guideline with a multitude of requirements is compiled.

Further research will focus on the financial effects of product development in regard of post-series supply. The consideration of the requirements of the post-series supply may generate additional costs in product development or during production. The benefits in contrast will be generated at the end of the life cycle, 10 or 15 years after production. Many companies have a short-term thinking and demand a return on investment in a few years. Due to the long-term effects an enterprise culture with a focus on sustainability is required for the successful implementation of the proposed methodology.

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Set Based Robust Design of Systems – Application to Flange Coupling

A.J. Qureshi, J.Y. Dantan, J. Bruyere, and R. Bigot

Abstract A set-based approach to design of mechanical systems is presented in the following text. Set-based technique allows keeping multiple alternatives alive during the design process while narrowing through the possibilities towards the most optimal solution. Using the Quantifier notion from QCSP (Quantified Constraint Satisfaction Problem), a formal expression for the problem has been developed. An algorithm using QCSP transformation through interval analysis has also been developed. In order to demonstrate the approach, an example of design of rigid flange coupling with a variable number of bolts and a choice of bolts from ISO M standard has been resolved and demonstrated.

Keywords Set based design · Robust design · QCSP · Quantifiers · Tolerance integration

1 Introduction

One of the challenges that the design engineers deal with during the early design phase of a system is lack of detailed information. In order to create a conceptual design, the design engineers create initial concepts based on the client's requirement. These concepts then compete with each other and are refined as more information becomes available during the product design cycle. In order to create the concepts the first task is to identify the functional requirements and define the main design parameters for the product. Once these parameters are defined the design process strives to find the appropriate values of these parameters such that an optimal balance between the desired functional requirements and constraints related to the product performance, quality and cost are achieved. Many design approaches exist which enable the design engineers to take the appropriate steps in order to reach this desired results.

Traditionally the design process goes through a point based design approach where individual stake holders in the design process offer their specific design solution to other participating interfaces which then further develops the design based on the available information. Often this process results in the reworks due to the downstream incompatibilities that are reported via feedback loop and therefore result not only in rework but also in increasing time spent before the design can be finalised [1].

"Set-based concurrent engineering" (SCBE) or set based design is an approach utilised by Toyota to pursue its design process. SCBE begins by broadly considering sets of possible solutions and gradually narrowing the set of possibilities to converge on a final solution [1]. SBCE process consists of development and communication of sets of solutions in parallel and relatively independently instead of following a point based approach. These sets are then refined by elimination of set members that are not feasible, resulting in the narrowing of the possibilities. As the sets narrow, the depth and detail of information increases thereby refining the sets. Also the ability to take into account a number of sets concurrently instead of in a point wise approach enables to achieve a robust solution space which is less susceptible to a rework or rejection by other design interfaces.

In this chapter we present an approach for robust design of mechanical systems that is based on the set-based design approach. The approach presented relates to the domain mapping stage of the set-based design and relying on the set-based design approach objectives it provides robust solution of mechanical systems. This is achieved by using the quantifier notion from QCSP and Interval arithmetic to perform design space exploration and separate the admissible design solution spaces containing the robust solutions from

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the departing design space. The approach permits taking into account the design parameters and uncertainty/variation parameters associated to the design of system in forms of sets, either discrete or continuous as well as integration of different design stake holders (design and manufacturing) simultaneously in the design solution space exploration. The integration of uncertainty/variation within the design space exploration results in the solutions being inherently robust. An algorithm has been developed which treats the example of a rigid flange coupling design with ISO standard screws and demonstrates the approach.

2 Set-Based Robust Design

The main objective for robust design of a system is to design a system in such a way that its performance is not compromised beyond the minimum requirements in presence of variations and uncertainties in PLM as well as different environmental and other changing parameters. These uncertainties and variations can be classified into: Changing environmental and operating conditions; production tolerances and actuator imprecision; uncertainties in the system output and feasibility uncertainties. These uncertainties may be of deterministic type or probabilistic type or possibilistic type [2]. Robust design can be viewed as an optimisation approach which tries to account for uncertainties described above. Traditionally the robust design is performed via sensitivity analysis of a given solution to the variations and then adjusting the design parameters such that the performance of the system is according to the requirements in presence of such variations. Different approaches exist for robust design such as Taguchi [3, 4], robust optimization, axiomatic design [5] and variation risk management etc. which with help of deterministic or randomized approaches [2] allow the engineers to decide a robust parameter design of a system.

Set based design is an approach to engineering design in which different design alternatives are evaluated by reasoning and comparing different design solutions based on possibilities offered by alternative possible configurations of "SETS" of design parameters. Set based design aims to delay commitments to a particular design in favour of gathering information about problem and to reduce imprecision to levels at which indeterminacy is resolved [6].

The domain mapping phase of a Set based design methodology consists of mapping or exploring the design space for feasible regions while keeping multiple alternatives and looking for intersections of feasible sets as proposed by different design/manufacturing interfaces [1] which satisfy the required minimum number of constraints while ensuring robustness.

When viewed in terms of robust mechanical design, this translates into ensuring a choice of multiple design configurations, which may empower the design team to choose an appropriate solution while at the same time ensuring the robustness of the design with respect to the functional, as well as quality and cost constraints.

Essentially it means that the different stake holders in the design process may be able to communicate their feasible sets at the start of the design process i.e. the design engineering may communicate the sets of design parameters whereas manufacturing may communicate the sets of machining/process capability. The resulting design space consisting of the design parameter space and variation parameter space can then be explored for the feasible region. The intersection of the feasible design space can then lead to a possible solution and an intersection of design and variation space would lead to a solution which may be inherently robust.

Using the principle described above, the approach presented in this chapter provides a method to perform a simultaneous domain exploration of design and variation parameters, resulting in a robust solution.

2.1 Design as Constraint Satisfaction Problem

The design parameters are the key variables which describe the product as well as its behaviour. The design variables may be of the geometric nature, engineering nature or manufacturing nature and may deal with shape, configuration, material, manufacturing process etc. Each product has some main performance criteria to fulfil. These criteria are the design constraints, i.e. the minimum performance requirements. These design constraints are generally expressions consisting of the design parameters, and constants. In an engineering model, the representation of constraints may be algebraic equations or predicates, sometimes with a few additional logical constraints [7]. Essentially it can be viewed as solving a system of simultaneous equation for homogenous solution. The first approach of solving the system is based on an iterative, numerical algorithm. It may be used when the constraints are expressed as algebraic equations in implicit form ($f(x) = 0$). The mathematical problem is to solve this set of non-linear equations simultaneously [1]. Different iterative methods for solving such systems exist which may be generalized in the category of Constraint Satisfaction Problems (CSP).

2.2 CSP Adaptation To Uncertainty

A solution to a CSP generally seeks to identify the discrete point values or instances of research domains to evaluate a solution which satisfies the constraints. A set of these instances calculated in an iterative manner allow us to develop the final solution in terms of valid intervals which satisfy the constraints.

This approach is feasible for the point based design but in terms of a set based design the need arises to have a system in place that can address the sets natively, i.e. a group of information. In addition, the need to separately quantify the variables existentially or universally is also required to integrate the notion of uncertainty/variation in the system. In such cases, the solution calculated by help of conventional CSP techniques might not suffice and may not perform according to the desired performance level.

It is therefore useful to have a method which might integrate the incertitude in the system or in environment at an early design stage. In order to do so a methodology is being proposed which not only integrates the notion of uncertainty in the product but also enables quantification of the variables. As such the methodology being proposed allows the robust solution of a parametric design problem.

2.3 Quantified Constraint Satisfaction Problem Integration for Robust Design

Reference [8] The quantified constraint satisfaction problem (QCSP) is a general extension of the constraint satisfaction problem (CSP) in which variables is totally ordered and quantified either existentially or universally. This generalization provides a better expressiveness for modelling problems. Model checking and planning under uncertainty are examples of problems that can be modelled with QCSP.

The research in QCSP is recent. Bordeux and Montfroy [9] have extended the notion of Arc consistency of CSP to the QCSP. Mamoulis and Stergiou [10] have defined an algorithm for arc consistency for QCSP for binary constraints.

In this chapter, we demonstrate the effective application of the QCSP technique for integrating the notion of robustness in the Mechanical design process.

3 Problem Formalisation

As mentioned earlier, an engineering design model may be expressed as a system of equations which may be generalized as a CSP. The general representation of the CSP may be done as a triple:

$$\{\boldsymbol{V}, \boldsymbol{D}, \boldsymbol{C}\} \tag{1}$$

Where

$\boldsymbol{V}$= Set of variables
$\boldsymbol{D}$= Domain of the variables
$\boldsymbol{C}$= Constraints governing the variables.

In a general design problem, $\boldsymbol{V}$ represents all the design variables, $\boldsymbol{D}$ defines the total search space and $\boldsymbol{C}$ contains all the design/performance constraints. In CSP all the variables are existentially quantified, i.e. the interaction between the variables is existential and unique. This interaction is sufficient for modelling a parameter based problem but for the integration of the concept of uncertainty/noise, CSP modelling becomes complex. Modelling uncertainty and noise in a model stipulates that the variables be able to quantify universally i.e. the ability to individually condition the interaction between the different variables of a model. QCSP offer us this flexibility. A General QCSP can be expressed as:

$$\{QV, D, C\} \tag{2}$$

Where Q is a quantifier $\exists$ or $\forall$, $\boldsymbol{V}$ is $\boldsymbol{V}$= Set of variables

$\boldsymbol{D}$= Domain of the variables
$\boldsymbol{C}$= Constraints governing the variables.

The QCSP allows the designer to explicitly condition the variables with help of quantifier to define its interaction in the system.

3.1 Integration of QCSP with Robust Design

In order to integrate the general design problem with help of QCSP given in Eq. (2), we need to add the parameters of uncertainty to the design problem. Therefore the new system that emerges can be described as:

$$\{\mathrm{QV}, \mathrm{QN}, D, C\} \tag{3}$$

Where

QV= Quantified design variables
QN= Quantified noise or uncertainty variables.
$\boldsymbol{D}$= Domain of the variables
$\boldsymbol{C}$= Constraints governing the variables.

The emerging system can now be formalized mathematically to a robust solution. A brief description of terms is given in order to illustrate the following example.

- Design parameters "$\boldsymbol{v_i}$" are the parameters having an appreciable effect on the product performance and functional characteristic. These parameters maybe of a mechanical or geometric nature.
- The noise parameters "$\boldsymbol{n_j}$" are the variables which model the noise. These parameters are the measure of the uncertainty of different factors, which might impact the product performance and therefore the conformity of the product performance to the desired design basis.

Once these parameters have been designed, a model needs to be defined which embodies the relation between the product functional requirements, design basis and the above defined parameters. This is done with the help of the system of equations that model the mechanical behaviour of the system while taking into account the design as well as the noise parameters. The equation may be of the explicit or implicit form. In general they can be described in the following form:

$f(\boldsymbol{v_i}, \boldsymbol{n_j})$ is a function which defines the relationship between the desired product performance, the design parameters and the noise parameters.

3.2 Conditions for Solution

In order for a solution to be robust, it should respect the two global conditions concerning the design parameters as well as the noise parameters.

3.2.1 Condition for Existence of a Solution

The first condition for the existence of a robust solution is that; a solution must exist belonging to the domain of the design parameters such that the design constraints are satisfied. This can be defined as "At least one configuration of design parameters belonging to their respective domains must exist such that the functional requirements are fulfilled". It can be translated mathematically as:

$$\exists V \in D_V : D_{f(V)} \in D_{\text{Solution}} \tag{4}$$

Where $\boldsymbol{V}$ is the set of the design parameters belonging its respective domain $\boldsymbol{D_V}$.

3.2.2 Condition for Existence of a Robust Solution

The second condition for the existence of a robust solution is that; there must exist a solution satisfying the constraints with for all the values of design parameters within their domains while keeping in account all possible values of noise variables within their domains. This can be defined as: "For all the values of design parameters and for all the values of noise, the constraints must be respected". This can be mathematically translated as:

$$\forall_N \in D_N, \forall V \in D_V; D_{f(V,N)} \in D_{\text{Solution}} \tag{5}$$

These two conditions are verified for the successful existence of a solution.

An algorithm has been developed which permits solving this problem with help of usage of exhaustive search and interval analysis techniques by using interval analysis to search for robust solution in the sub search spaces created by the algorithm.

4 Algorithm

Having developed the integration of QCSP with robust design and the subsequent mathematical expressions establishing the basis for the robust solution in terms of the universal and existential quantifiers, in this section we will explain the basic concepts related to the transformation of the developed theory in an applicable algorithm which can then be programmed and run on computer to obtain the solution for a given problem.

The main challenge in the transformation of the robust design with quantifier expression is the expression of quantifiers. For this purpose a number of approaches were explored out of which transformation into an interval analysis problem was adopted. In order to apply the developed approach with help of interval analysis we need to define some fundamental notions [11].

Definition 1 The design variables involved in the problem are expressed in forms of intervals except in case of design variables of discrete nature. Each interval is a set of connected reals with lowest and upper bounds as floating point intervals. The interval $\boldsymbol{I}$ for a design variable $\boldsymbol{x}$ defined as a real number would therefore be represented in form of an interval as follows:

$$I_x = [\underline{x}, \bar{x}] \equiv \{x \in R | \underline{x} \leq x \leq \bar{x}\} \tag{6}$$

Definition 2 A Cartesian product of $\boldsymbol{n}$ intervals $B = I_1 \times \ldots \times I_n$ is called a box; a domain $\boldsymbol{D}$ is either an interval $\boldsymbol{I}$ or a Union $\boldsymbol{U}$ of disjoint intervals.

Definition 3 The set of the initial domains of all the involved variables is D-BOX. A D-Box BD with arity $\boldsymbol{n}$ is the Cartesian product of $\boldsymbol{n}$ intervals where $\boldsymbol{n}$ is the number of the design variables involved in the problem. It is denoted by $\langle I_{x1}, I_{x2}, I_{x3}, \ldots I_{xn}\rangle$ where each I is an interval.

$$\text{BD} = \{I_{x1}, I_{x2}, I_{x3}, \ldots I_{xn}\} \tag{7}$$

Definition 4 The set of the intervals of sub domains of the variables SD-BOX. A SD-Box BSD with arity $\boldsymbol{n}$ is the Cartesian product of $\boldsymbol{n}$ intervals where $\boldsymbol{n}$ is the number of the design variables involved in the problem. It is denoted by $\langle I_{x1}, I_{x2}, I_{x3}, ...I_{xn}\rangle$ where each $\boldsymbol{I}$ is an interval. BSD results when a D-BOX is split.

$$\begin{aligned} &\mathrm{BSD} \subseteq \mathrm{BD} \\ &\mathrm{BSD} = \left\{ \begin{matrix} \langle I_{sx1}, I_{sx2}, I_{sx3}, ...I_{sxn}\rangle \,|I_{sx1} \subseteq I_{x1}, \\ I_{sx2} \subseteq I_{x2}, ...I_{sxn} \subseteq I_{xn} \end{matrix} \right\} \end{aligned} \tag{8}$$

Definition 5 (Benhamou et al. [11]) An Interval extension of $f : \mathbf{R}^n \rightarrow \mathbf{R}$ is a mapping $F : \mathrm{I}^n \rightarrow \mathrm{I}$ such that for all:

$$\begin{aligned} &I_{x1}, I_{x2}, I_{x3}, ...I_{xn} \in \mathrm{I} : \\ &x_1 \in I_{x1}, ...x_n \in I_{xn} \Rightarrow \\ &f(x_1, ..., x_n) \in F(I_{x1}, ..., I_{xn}) \end{aligned} \tag{9}$$

An interval extension of a relation $\rho \subseteq \mathbf{R}^n$ is a relation $R \subseteq \mathrm{I}^n$ such that for all:

$$\begin{aligned} &I_{x1}, I_{x2}, I_{x3}, ...I_{xn} \in \mathrm{I} : \exists x_1 \in I_{x1}, ...\exists x_n \in I_{xn} \\ &\mathrm{s.t.}(x_1, ...x_n) \in \rho \Rightarrow (I_{x1}, I_{x2}, I_{x3}, ...I_{xn}) \in R \end{aligned} \tag{10}$$

The function to be extended may be an inequality or equality.

The software used to program the algorithm and later test it for the example mechanism is Mathematica®. Mathematica® contains the built in operators for the Universal quantifier and the Existential quantifiers. Initial applicability tests for the quantifier expression were undertaken while using these operators. The usage of these operators is however restricted to rudimentary verification only and soon becomes unfeasible for any applicability to even a simple mechanism. In order to address this, two alternative possibilities i.e. Transformation to interval analysis and transformation into an optimization problem were studied. Among these two techniques, transformation of quantifiers with help of interval analysis was found to be fast and efficient therefore this technique was used. The algorithm is divided into three main steps:

The first step takes the BD as an input and is responsible for dividing the BD in BSD and assigning the BSD to be evaluated to the next step for the evaluation of the existence of robust solution. Once this step is concluded the results are stored in the results module which then processes the results to present the domains related to the robust solution. A detailed flow chart describing the algorithmhas been presented in Fig. 1.

The initial design domain specified by the design engineer is encapsulated in BD and is used as the starting search space for the algorithm. The algorithm then proceeds by the dividing BD in the number of BSD as specified by the design engineer. Each of these BSD is then successively passed on to the evaluation module for evaluation of box consistency existence of robust solution.

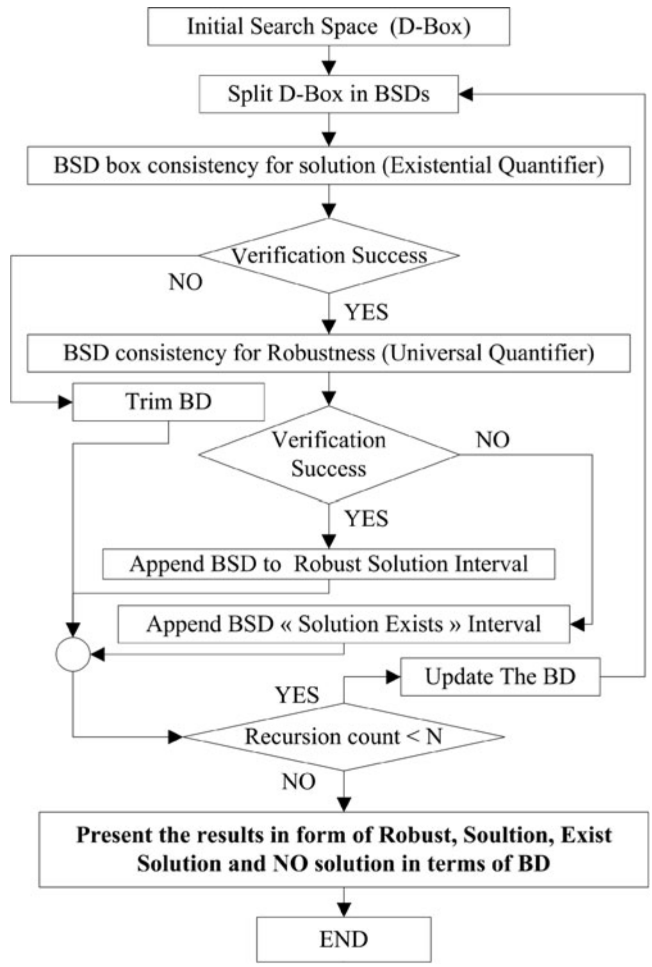


Fig. 1 Algorithm flow chart

The evaluation module is responsible for evaluation of the consistency of the BSD for finding the existence of robust solution. This module uses the two conditions expressed earlier to evaluate the robustness of the BSD under consideration. Using the quantifier conditions the relevant constraints arising from the transformation of the real functions f into the interval based functions F involving the interval variables obtained from the transformation of the real variables to interval variables are then used for evaluating the consistency of BSD. The functions maybe explicit or implicit expressed in terms of an equality or inequality.

The quantifier conditions are translated by the following mathematical expressions:

Condition for box consistency of a solution: The Eq. (4) expresses the existence of solution in terms of the existential quantifier. Its transformation into the algorithm with help of the interval analysis stipulates that BSD should be consistent for the given constraints:

$$\begin{aligned}&I_{x1}, I_{x2}, I_{x3}, \ldots I_{xn} \in I: \\ &x_1 \in I_{x1}, \ldots\ldots x_n \in I_{xn} \\ &\operatorname{Max}(F(I_{x1}, \ldots, I_{xn})) \vee \\ &\operatorname{Min}(F(I_{x1}, \ldots, I_{xn})) \in D_{\text{solution}}\end{aligned} \tag{11}$$

For the BSD validated through the check performed by Eq. (4) robustness check is performed by the BSD consistency in presence of noise as stipulated by Eq. (5)**.** This translates as following:

Condition for box consistency of a robust solution: In presence of noise/uncertainty denoted by $N = \{n_{x1}, n_{x2}, \ldots, n_{xn}\}$, where $\boldsymbol{n_{xi}}$ is the noise/uncertainty related to the design variable $\boldsymbol{x_i}$, a solution is robust if the BSD is box consistent in presence of the noise parameters:

$$\begin{aligned}&I_{x1}, I_{x2}, I_{x3}, \ldots I_{xn} \in I: \\ &n_{x1}, n_{x2}, n_{x3}, \ldots n_{xn} \in N: \\ &x_1 \in I_{x1}, \ldots\ldots x_n \in I_{xn} \\ &\operatorname{Max}(F(I_{x1}, \ldots, I_{xn}, n_{x1}, n_{x2}, \ldots n_{xn})) \wedge \\ &\operatorname{Min}(F(I_{x1}, \ldots, I_{xn}, n_{x1}, n_{x2}, \ldots n_{xn})) \in D_{\text{solution}}\end{aligned} \tag{12}$$

The transformation can be depicted by Fig. 2 which shows the transformation of the components of the quantified Constraint satisfaction problem by interval analysis.

The quantified variables are replaced by the interval variables as shown in the diagram where each variable is assigned a upper and lower bound taken from the extremities of the interval. This operation is carried out for all the involved variables including the noise and design variables. Similarly the constraints are also transformed into interval constraints which are then able to take the interval variables. The constraints are then evaluated for the condition of existence of solution. If a BSD does not contain any solution, it is discarded and subsequently BD is reduced. Another BSD is then analyzed for the existence of solution. If an existence solution is found then this BSD is evaluated for global hull consistency of universal quantifier in presence of the uncertainty. In case of a successful evaluation the BSD saved as a robust design solution space. However if the space fails to evaluate for the consistency for robust solution, it is further decomposed into BSD until the robust solution space has been found. This process is repeated until the totality of BD has been explored for the robust solution.

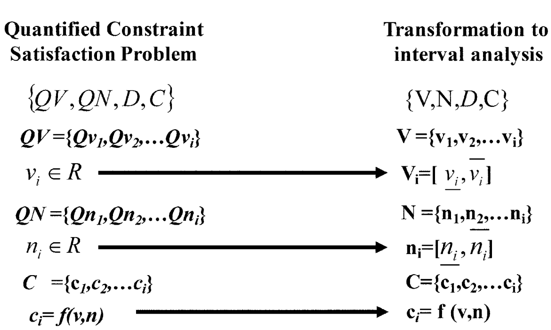


Fig. 2 Quantifier transformation

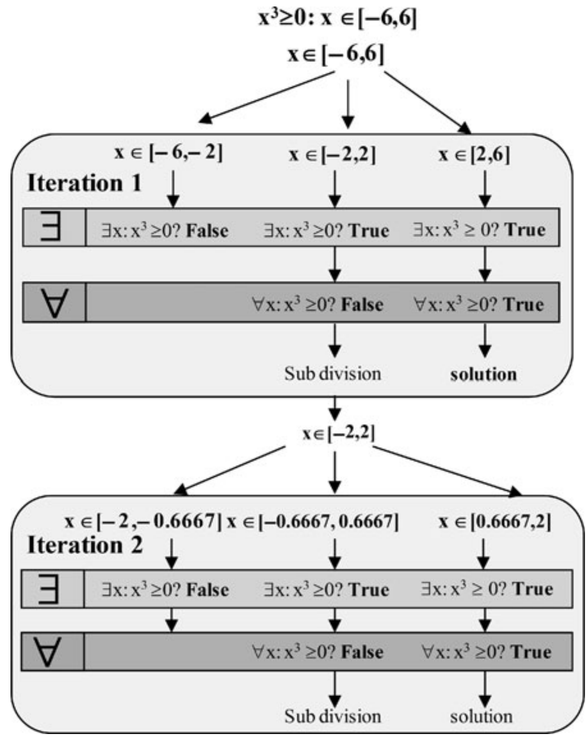


Fig. 3 Example with a single variable and single constraint

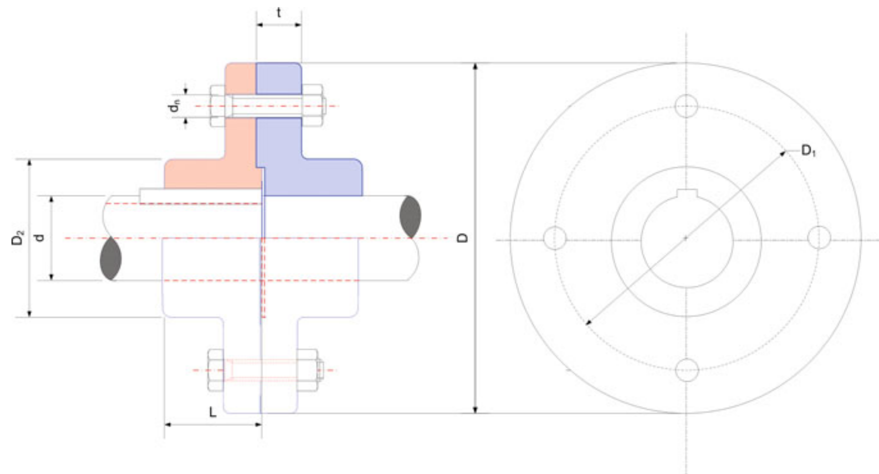
The final module stores the results as they are produced by the evaluation module. The results module serves two purposes. Firstly, it supplies the updated situation of the search during each iteration to the evaluation module and secondly at the end of the simulation it presents the results in terms of the search space partition in terms of space without solution, space with robust solution and the space with a probable solution.

The Fig. 3 illustrates the algorithm with help of a simple example. The BD is [–6,6] which is then successively evaluated for the universal and existential quantifier in order to ascertain the consistency of the BD.

5 Application

In order to illustrate the approach an example has been tested. The example chosen is a design decision process regarding the dimensions of a Flange coupling as well as choice of bolts. The example is shown in Fig. 4 and is a rigid flange coupling used to connect two shafts for torque transmission in varied applications. It may be used to connect a prime mover such as a small steam turbine or an electric prime

Fig. 4 Model assembly



mover such as a motor to the driven machinery such as a pump or a compressor etc. The prime design consideration is to transmit the power between the connected shafts in a reliable and safe manner with lowest possible loss of transmission as well as the optimum cost versus quality balance. The above mentioned factors being the prime considerations of the design, the approach presented earlier will be used to integrate these requirements for a solution consistent with the reliability, performance and safety requirements while being economic at the same time.

5.1 Design Constraints

Once the requirements have been decided, the design constraints can then be laid down to ensure the adherence of the design process to the required criteria. Following main relationships can be established.

- The Performance requirement is translated by the torque to be transmitted.
- The safety and reliability requirement is translated by designing the coupling in a robust way to ensure the capacity of the coupling to transmit the torque while remaining within the zone of safe mechanical operations as given by the torque requirements and taking into account the uncertainty related to the design parameters.
- The cost versus quality factor to be evaluated by integrating the cost of material as well as the cost of the bolts.

Having defined the requirements and qualitative constraints, we can now proceed to develop the basic mathematical relations dictating the developed constraints. The description of the symbols and abbreviations used in the equation can be founding in appendix at the end of the article.

The most important design requirement being the torque transmission, the design constraints are oriented towards three main areas:

- Mechanical constraints related to the flange torque transmission capacity.
- Mechanical constraints related to the bolt torque transmission capacity.
- Dimensional and geometric constraints ensuring the assembly and insertion of the bolts and their tightening.

The translation of the above three requirements results into 10 constraints which are:

Mechanical constraints related to the flange torque transmission capacity

$$T_{\text{hub}} = t(\pi D_2)\tau_{\text{f}}\frac{D_2}{2},\ T_{\text{hub}} \geq T \tag{13}$$

$$T_{\text{fraction}} = i\mu F_{\text{b}} r_{\text{m}},\ T_{\text{fraction}} \geq T \tag{14}$$

$$\tau_{\text{f}_{\text{calculated}}} = \frac{T16}{\pi}\left(\frac{D_2}{D_2^4 - d^4}\right), \tau_{\text{f}_{\text{calculated}}} \leq \tau_{\text{f}} \tag{15}$$

Mechanical Constraints related to the bolt torque transmission capacity

$$T_{\text{b}_{\text{Shear}}} = i\left(\frac{\pi d_{\text{n}}^2}{4}\right)\tau_{\text{b}}\frac{D_1}{2}, T_{\text{b}_{\text{Shear}}} \geq T \tag{16}$$

$$T_{\text{b}_{\text{bearing}}} = i(d_{\text{n}}t)\sigma_{\text{b}}\frac{D_1}{2}, T_{\text{b}_{\text{bearing}}} \geq T \tag{17}$$

$$i_{\text{m}} = 3, i \geq i_{\text{m}} \tag{18}$$

$$\begin{aligned}
&\sigma \mathrm{eq}_{\max} = \sqrt{\sigma^2_{\mathrm{b}_{\max}} + 3\tau^2_{\mathrm{b}_{\max}}} \\
&\tau_{\mathrm{b}_{\max}} = 16\frac{C_1}{(\pi d^3_{\mathrm{ts}})} \\
&C_1 = F_{\mathrm{b}}(0.16p + 0.583d_2 f_1) \\
&d_{\mathrm{ts}} = d_{\mathrm{n}} - 0.938194p \\
&\sigma_{\max} = \frac{F_{\mathrm{b}}}{A_{\mathrm{t}}} \\
&F_{\mathrm{b}} = \alpha_{\mathrm{s}} F_{0_{\min}} \\
&0.9\sigma_{\mathrm{y}} \geq \sigma \mathrm{eq}_{\max}
\end{aligned} \tag{19}$$

Dimensional constraints ensuring the assembly and insertion of the bolts and their tightening.

$$D_1 \geq D_2 + 2b_{\mathrm{A/C}} + 2m_{\mathrm{b}} \tag{20}$$

$$D \geq D_1 + 2b_{\mathrm{A/C}} + 2m_{\mathrm{b}} \tag{21}$$

$$s_{\mathrm{c}} = 2\pi \frac{D_1}{i} - b_{A/C}, s_{\mathrm{c}} \geq p_{\mathrm{b}} \tag{22}$$

Table 1 Shows the main design parameters used in the example with their starting sets and types.

Out of the 14 design parameters selected above, 7 are continuous variables whereas 7 are discrete. The discrete variables may have additional attributes such as different material properties related to a specific bolt/flange material.

In order to model the noise/uncertainty in the model, eight noise generating variables are defined related to the design variables as shown in Table 2.

Table 1 Design Parameter sets and types

Variable	Type	Description	Domain
t	Real	Thickness of flange	[0.0015,0.02]
D	Real	Outside diameter of flange	[0.035,0.13]
D_1	Real	Bolt circle Diameter	[0.03,0.11]
D_2	Real	Hub outside diameter	[0.03,0.09]
m	Real	Coeff. of friction b/w flange surfaces	[0.1,0.55]
f_1	Real	Bolt coeff. of friction	[0.04,0.10]
f	Real	Bolt Preload force	
i	Discrete	Number of bolts	[3,4,5,6]
d_n	Discrete	Bolt nominal diameter	ISO M bolts
mat_b	Discrete	Bolt material	Blot Classes
p	Discrete	Thread pitch	ISO M bolts

Table 2 Uncertainty/variation variables sets and types

Variable	Type	Description	Domain
Δt	Real	Thickness of flange	[–0.001,0.001]
ΔD	Real	Outside diameter of flange	[–0.001,0.001]
ΔD_1	Real	Bolt circle Diameter	[–0.001,0.001]
ΔD_2	Real	Hub outside diameter	[–0.001,0.001]
$\Delta\mu$	Real	Coefficient of friction between flange surfaces	±2.5%
Δf_1	Real	Bolt coefficient of friction	±2.5%
Δf	Real	Bolt Preload force	±25%

5.2 Approach

Once the set of constraints and the initial sets for the design parameters and the noise variables have been defined, the design problem is translated with help of the quantifiers for the evaluation of box consistency for existence of solution and consistency for a robust solution. The quantifier notion is then translated in terms of computable form by help of interval mapping of each variable set to a corresponding interval and transforming the constraints into the interval form using the principles described earlier.

For consistency check for existence of solution, the constraints defined in (Eqs. (13), (14), (15), (16), (17), (18), (19), (20), (21), and (22)) are transformed into interval functions whereas in order to evaluate the robust solution consistency, the design constraints are modified by addition of the uncertainty/variation set to the corresponding design parameter in the constraint resulting in the interval based robust design constraints. Using the application of Eqs. (4) and (5) via their interval transformations through Eqs. (11) and (12), all the BSDs and hence BD is evaluated. If a BSD does not fulfil any box consistency expression, it is discarded as space without any solution. However if the solution box consistency expression Eq. (11) is validated, the BSD is regarded as having the possibility of solution and its evaluated for the box consistency of a robust solution via expression Eq. (12) which also integrates the noise parameters. If the latter expression is also validated then the space is regarded as a robust solution space else it is sub divided and the process is repeated.

The results obtained for the given example are shown in form of three dimensional projections between three variables $\boldsymbol{D}$, $\boldsymbol{D_1}$ and $\boldsymbol{D_2}$. In Fig. 5a–d, the main box represents the total BD projected in terms of the three selected variables with the starting intervals along their respective axes.

In Fig. 5a, light grey boxes after the first iteration show the possible search space (BSDs) marked by the algorithm for a consistency for existence of a solution. Figure 5b, shows the sets of robust solution within the search space in form of dark grey boxes found after the first iteration consistent for a robust solution. In a similar fashion Fig. 5c and d show results for consistency of solution and consistency of robust solution in 2$^{\mathrm{nd}}$ iteration. The choice of the discrete variables can also be seen in a similar way (Fig. 6).

6 Conclusion

The work presented in this chapter proposes a new approach of concurrent engineering design with parallel exploration of design parameters as well as uncertainty and variation parameters of the mechanical systems with help of the set based design and Quantifier notion. Addressing the design

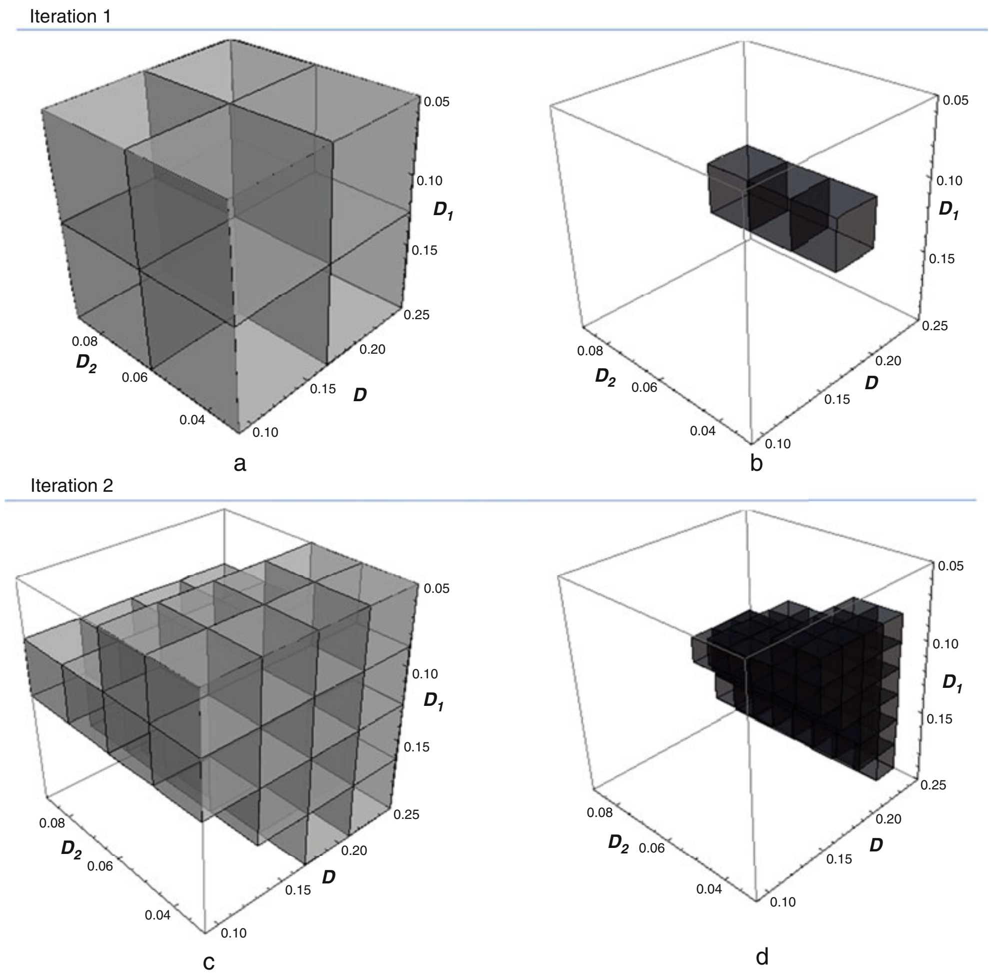


Fig. 5 (**a**)-BSDs for existence of solution (1st Iteration), (**b**)-BSDs for robust solution (1st iteration), (**c**)-BSDs for Existence of Solution (2nd Iteration), (**d**)-BSDs for robust solution 2nd iteration

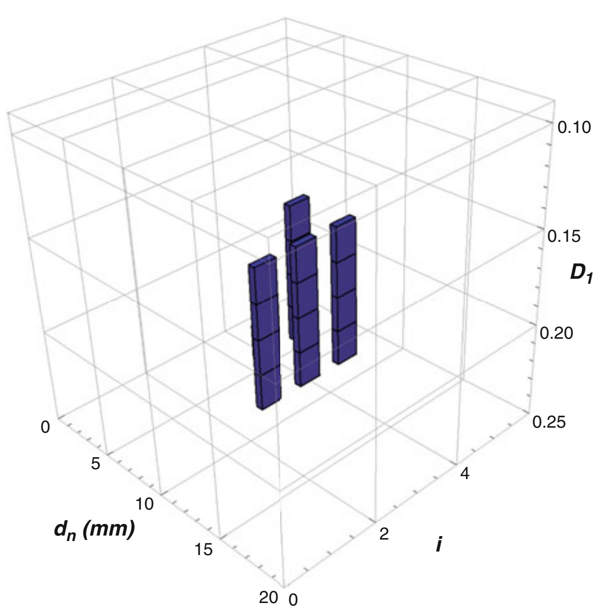


Fig. 6 Projection between real and discrete variables

parameters in terms of sets allows a greater freedom of design choices and their evaluation.

When the robustness sets are also included in this paradigm, the resulting design space/variation space intersection provides us with a solution that is inherently robust and can accommodate the changes due to different variations such as manufacturing variations which may be voluntary or involuntary, small variations in the material properties as well as variations that may result to error such as bolt preload force in the previous example.

Each robust solution in the approach presented is a set of possibilities which performs according to the given design requirements. The approach also gives the designer a greater freedom over optimising the design solution with respect a given constraint as the solution is presented over an envelope of different values of design parameters.

The quantifier notion used to express the requirements allows us to explicitly define the design requirements on the individual variables involved in a product design phase. The approach proposed in this chapter allows the design engineer to integrate the notion of uncertainty in product design right from the early design phase and helps him to find the sensitive as well as the robust design regions in the possible product design search space. Different types of noise parameters can be treated by the proposed approach. In the treated example, the types of the uncertainties are of three types i.e. dimensional uncertainties/variances, geometric uncertainties and material property uncertainties. Also, from a mathematical point of view two different types of variables and uncertainties have been treated i.e. Discrete and continuous. The usage of interval analysis for conversion of the problem provides an appreciable gain in the computational time cost.

Appendix

Description of abbreviations and symbols

A_t = Tensile Stress Area
$b_{A/C}$ = Bolt head length across corners
C_1 = Torion moment in bolt due to preload
D = Outside diameter of flange
d = nominal diameter of the shaft/hub internal diameter
D_1 = Bolt circle diameter
D_2 = Hub outside diameter
d_2 = Pitch diameter of threat
d_n = Bolt nominal diameter
d_{ts} = Diameter of stress area
f_1 = Friction coefficient between the bolt and the flange
$F0_{min}$ = Minimum bolt tightening torque
F_b = Tension load in each Bolt
i = Number of bolts
m_b = Minimum bolt center distance from edge
p = Pitch of thread
p_b = tool clearance
r_m = Mean radius of surface
S_p = Proof Strength of bolt
T = Torque to T_{hub} = Torque capacity based on shear of flange at the outside hub diameter
$T_{friction}$ = Torque transmission capacity due to friction
Tb_{shear} = Torque transmitted through bolts in shear
$Tb_{bearing}$ = Torque capacity based of bearing of boltsbe transmitted
t = Thickness of flange
α_s = Accuracy factor of tightening tool
σ_y = Bolt yield strength
σ_b = Design stress in bolts
σeq_{max}= Von Mise stress
$\sigma_{b_{max}}$ = Max. tensile stress in bolt
μ_s = Coefficient of friction between flange surfaces
τ_t = Design shear stress in flange
τ_s= Design shear stress in shaft
$\tau_{b_{max}}$ = Max. torsional stress in the bolt

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A Product Life-Cycle Oriented Approach for Knowledge-Based Product Configuration Systems

V. Schubert, H. Wicaksono, and S. Rogalski

Abstract Faced with increasing complexity in the global economy, a timely and accurate operation of the market demands an accelerated harmonization of customer and manufacturer perspective in the quotation phase through product configuration systems. An approach for knowledge-based product configuration through the integration of experience and knowledge from the product use phase is presented below. The goal of this approach is to enable a faster and software-controlled harmonization of the different customer's and the manufacturer's points of view during the pre-contract phase. Therefore a case-based reasoning method was developed to be integrated in a rule-based product configuration system. It allows a faster ascertainment of customer needs and thereby provides accurate and complete configuration of the provided products.

Keywords Product life cycle · Product Configuration · Requirements Engineering · Case-Based Reasoning

1 Introduction

Since many manufacturers have optimized the modularity of their product range in order to offer a wide product variety without increasing the internal complexity, the rapid changes of social, technical, and economic conditions in the market pose major challenges for manufacturers to deal with the external complexity of customer requirements. It is important for them to understand how the dynamic customer requirements can be correctly and completely interpreted and processed. Inadequately specified or conflicting requirements often lead to an unnecessary rise in cost caused by subsequent adjustments or even further customer dissatisfaction. Furthermore, manufacturers and customers have different perspectives on a product. Manufacturers have the perspective related to product development. Customers have the perspective based on product use

During the proposal phase, it is crucial to align these two perspectives. However, the knowledge base for supporting alignment is also often incomplete and not explicitly available. Customers often have unclear requirements, which sometimes do not correspond to their actual needs or conditions. Sources of potential problems are identified late and thus result in modifications or corrections in the products. Because of the high number of variants and possibilities in product realization, it is difficult for manufacturers to find the optimal solution for given requirements and technologies, even by reutilizing already realized projects. Strongly diverging perceptions on the essential product requirements at the first contact between manufacturer and customer result in time-consuming and costly iterative agreement procedures. An increasing number of customer requests, which causes time-consuming agreement processes, leads to a demand for an information technology supported method. The method should shorten the information path and iteration from manufacturer to customer and vice versa.

2 Status and Related Works

In the pre-contract process, the dependencies between constructive-technological manufacturing possibilities targeted at individual customer's wishes and their situational context should be considered. In particular, manufacturers are faced with a number of problem domains, which complicate the timely recognition of conflicts between the expressed customer requirements and required product properties, as well as conflicts among product properties themselves. Recently, knowledge-based configuration systems are used to constrain the selection of product property variations. By using these systems, manufacturers only check the conflicting specifications of the product. Since purchasing decisions are subject to much more complex requirements of

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customer-specific circumstances, such as use and integration of the product, additional comprehensive requirement gathering and analysis should be performed as a base for product configuration. This connection is usually done without information technology support.

In previous research, there have been only a few satisfying solutions in product configuration concerning an accelerated harmonization of customer and manufacturer perspectives and mainly focusing only on the product knowledge [1, 2]. The reason for this is the lack of a holistic approach, enabling a faster gathering of customer requirements by using continuous feedback from the product use phase. Due to the increase of products combined with product-accompanying service as an information source, the product use phase has received growing attention [3]. Product-accompanying services enable manufacturers to obtain a well-directed information retrieval [4]. In many approaches, the knowledge generated in this way is, however, predominantly product-related. To achieve harmonization of customer and manufacturer perspectives, in order to reduce the effort for changes and adjustment during the tendering phase, the knowledge base of the configuration systems needs to be extended to include knowledge from the product use phase to check the consistency of the requirements.

For that purpose, sales and service-oriented Customer Relationship Management (CRM) functions have to be combined with Product Data Management (PDM) functions in an engineering domain to get a more closed-loop lifecycle oriented Requirements Management (RM). Thus assuring a structured and function oriented documentation of customer requirements.

3 Approach

In the approach developed by "FZI Forschungszentrum Informatik", a hybrid rule- and case-based configuration system is supported by the knowledge base of a case-based Product Life Cycle Management (PLM) concept. In this concept we include a continuous recirculation process in providing and controlling feedback information (also called field data) from internal and external knowledge domains of a company [5–7] to enable closed-loop life cycle oriented requirement engineering. The concept builds on current PLM models, which mostly only deal with product types during the internal processes of the company and rarely consider the information from the product use phase, through product case-studies, as applied in the approach from Abramovici et al. [8], linked to domain model cases of the individual customer's environment or so-called "Feedback Reference Objects" (FRO). For each purchased product, a FRO is initialized from the PLM-meta-model as instantiated objects of "product", "customer", and "context". Hence, it represents the corresponding profiles of the individual product and circumstances of the customer. It includes the situational dependencies; more specifically the customer's future product usage which consists of environment, application, integration parameters and also customer profile for every delivered product.

3.1 Feedback Reference Objects

The corresponding FRO's build the foundation for knowledge gathering from product use information such as product impact (e.g. customer benefits), product state in its structure (e.g. maintenance and modification), behavior (e.g. condition monitoring) and contextual factors (e.g. product surroundings). In case of a wider product range with different types of products, the knowledge gathering using the FRO is done for every specific type of product within its realized variants.

The resulting data models are used for a semantic integration in an ontology-based product-use-oriented requirement model, representing the corresponding dependencies between the different customers and manufacturers perspectives. Ontology is used in knowledge based application to support knowledge visualization, knowledge search and retrieval and also to serve as the basis for information gathering and integration [9]. In the approach presented in this chapter, ontology is used to model the requirements, products, customers, and usage context profile, in order to retrieve the knowledge needed to provide the optimal product configuration, which is suitable for the customer and which fulfills the requirements.

Moreover, the ontological analysis can clarify the structure of knowledge and provide a common understanding of any stake holders involved in the development and use phases. In order to be able to apply the knowledge from the product use phase in the tender phase, this integration concept is used to capture customer-, product-use-specific requirement models during the product-use-phase and, afterwards, to provide case- and rule-bases for the new product's configuration.

The cycle of building knowledge is divided into three steps: FRO creation, knowledge enrichment and its use in the product configuration. In the second step (knowledge enrichment), a so-called feedback process is divided into the acquisition phase required to collect information formally, the analysis phase and the integration phase.

Product configuration establishes the starting point of FRO creation, which refers to product-, customer- and context-profiles. The objects representing the available products and their structures, available customers and possible contexts are created initially by a tool called DIALOG business editor. The tool allows the creation and editing of knowledge elements, which build the knowledge base.

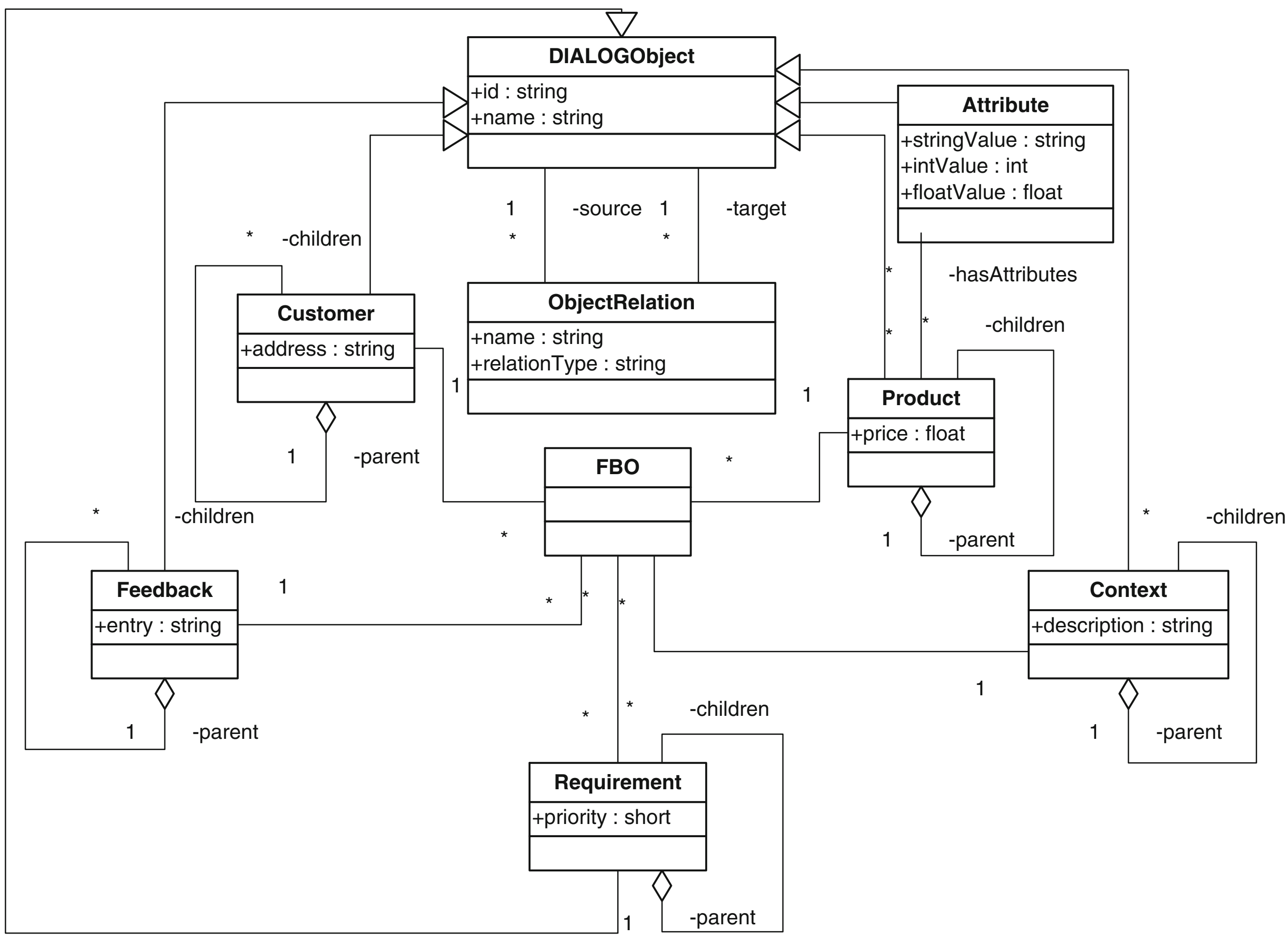

Fig. 1 Class diagram of the "Feedback Reference Object" (FRO)

- Product knowledge contains information about the architecture of the product, including the structure (modular BOM) and dimension, characteristics and features of the product itself and each component. It also contains rules for describing the assembly of the product, how or in which position the product components are placed when building the product. Hence it defines the constraints between product components and which components are not able to work together when they are used to construct the product. Product knowledge also describes the type hierarchy and the allocation of each product component in the type of hierarchy.
- Customer knowledge comprises customer-related information, such as preference data, purchasing power or business information. It can also contain customer grouping based on certain criteria, for example location, type of business or type of contract.
- Context knowledge consists of the main product surroundings such as environmental parameters, usage parameters, and peripheral parameters. Environmental parameters describe the circumstances in which the product is used, such as temperature and humidity, which can affect the function of the product during its utilisation. Usage parameters describe what the product is used for, and peripheral parameters describe other external components into which the product has to be integrated and on which the product function depends.

As described by the class diagram in Fig. 1, the self-referencing class with parent-children relation of context, product, and customer classes allows for a tree structure representing hierarchical classification. The ObjectRelation class which is related to the super class DIALOGObject, provides the possibility of semantic relations between any objects The cycle of building knowledge can be divided into three parts as shown in Fig. 2: creation, enrichment and usage. The phase of enrichment will be turned into the acquisition phase which is required to collect information and analyze feedback.

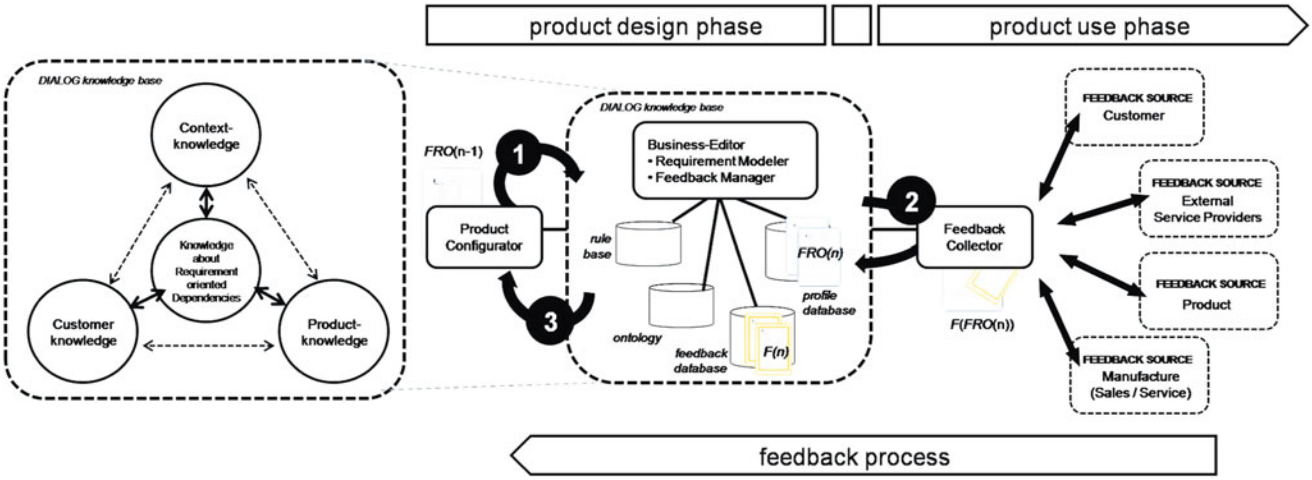

Fig. 2 Feedback process for knowledge building

3.2 Feedback Process

The starting point of the Feedback Process is the creation of the FRO, which includes the structural description of the product-, customer-, and context-profiles, built by the product configuration (Fig. 2, step 1). The product configurator is a software tool used by sales personnel or customers to configure products and their components during the pre-contract phase. A product and its components can be configured based on the available structures and components which have been defined using the business editor. Customer's usage contexts of the intended product are specified in the product configurator and are based on available contexts in the knowledge base. FRO's are considered to be instantiated once the product has already been configured and then purchased, i.e. the contract signed. The instantiated FRO's refer to the following objects:

- Customer objects: objects containing the profile of the purchasing customer. The customer profile is recognized automatically when the customer logs into the product configurator or when sales personnel find the customer ID in the product configurator.
- Product object: object representing the purchased product.
- Context objects: objects corresponding to usage contexts, which are specified using the product configurator.

FRO's exist during the product use phase. The instantiated FRO's are used as the starting point for building the knowledge base as the core of communication between customer and manufacturer.

The FRO's involving a specific customer or a particular product can be easily searched for and obtained. Other related objects can also be retrieved by performing a semantic search based on the ontology model.

The enrichment of the FRO occurs in a feedback collector which continuously collects active and passive feedbacks (Fig. 2, step 2). Feedback entries using the feedback collector can be entered by customers themselves, service or sales staff, or external service providers. Feedback can be generated automatically by the product as well, for example in the form of log files.

In the feedback collector, the feedback entries are associated with the available instantiated FRO's by considering in what context the product is used when the feedback is specified. The class diagram showed in Fig. 1 also describes the association of the FRO with the feedback entry. If there are changes in context or customer profile when the feedback entries are specified using feedback collector, the FRO's should be updated. If the required new context does not exist yet, a new context should be created using the business editor. This operation enriches the knowledge base of the system. The business editor user is notified by the feedback collector if the enrichment of the knowledge base is required.

In the phase of feedback analysis, the knowledge will be revealed from the collected information and its representations within the semantic requirement model (see Fig. 2, step 3). The feedback entries are also analyzed in order to enrich the semantic relations in the knowledge base, which are represented as ontological relations. From the feedback entries, it may be discovered that while a particular product works well in a certain context, it might not in another context. Thus semantic relations between the product attributes and contexts can be built.

The total FRO's form the case-base used for the product configuration (Fig. 2, step 3) as a base for searching for equivalent profiles and for requirements for systematic queries for relevant customer and context-specific factors, by mapping the initial requirement quantity within the semantic model [10]. These conclusions will be developed into specifications for each customer-related requirement quantity, so that its dependencies and inconsistencies, which are important for the product configuration, can be detected.

The product characteristics satisfying or supporting the requirements which emerged from the ontology query exhibit the most important parameters. The parameters are regarded as weighting factors for the similarity measure to broaden the range of the already selected product specifications and to define the rule base. With automated requests from the customer and context profile parameters, the interferences are called to the prime customer-, context- and product features through the semantic requirements model. After searching for similar context- and customer-profiles, an optimal product is determined within the scale of cost and customer review. Starting from this point, component-based configuration recommendations can be made (Fig. 3). If there is no applied product profile, all parameters based on the optimal product profile will be tested through construction-based rules and transformed to a new product profile in accordance with the requirement model specifications. If the product is purchased, a FRO is created again keeping the case-base up to date.

The first application has been demonstrated by implementing the approach. Its prototype enables the first knowledge-based product configuration through the implemented DIALOG feedback collector to directly access of field data. Thereby, service staff and customers can enter feedback to supplement information from the automated condition controller of the product after an evaluation of the requirement model and the profile's control system has been done. The web-based DIALOG product configurator is available to support sales staff by providing a faster and safer configuration.

4 Conclusions and Outlook

The approach described in this chapter has been developed during the first year of the project DIALOG funded by the German government. The approach introduces a hybrid method of rule-based and case-based analyses to find an optimal product configuration, which allows the thorough satisfaction of customer's needs. The analyzed product feedback data from different sources during the product use phase is utilized to continuously enrich the knowledge base including the requirement model. Customers' requirements, which are often not completely and correctly expressed, can still be recorded and processed by utilizing an ontology-based requirement model. The semantic search in the ontology requirement model delivers the most important parameters in reducing the computation complexity of the genetic algorithm used. This algorithm forms part of the case-based reasoning method in finding an optimal product configuration corresponding the customers' needs. The approach can

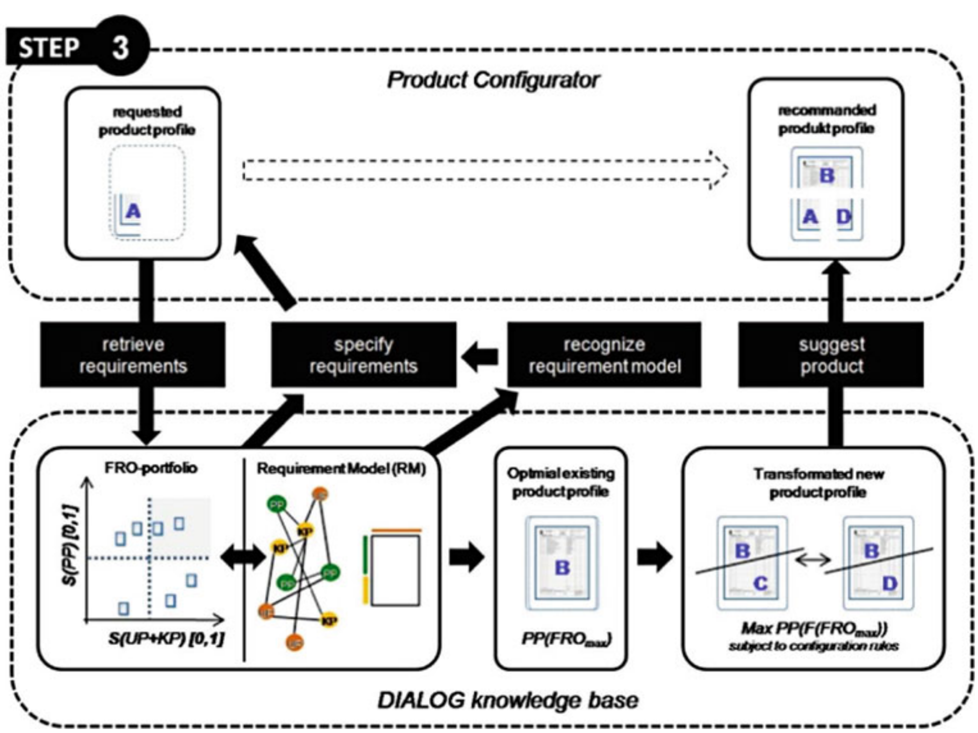

Fig. 3 Knowledge-based product configuration

be integrated into the requirement management through the identification of requirements and solution ideas from the field as well as in product development.

In addition to the concept described in this chapter, a software prototype representing proof of the approach was developed. With the final realization of the approach, SME's are expected to be able to improve their process in customer service management. Customers can be more easily and systematically integrated into the SME's product development. Due to the virtualization of the entire customer and manufacturer domains, the issues and vulnerabilities related to product development process can be dealt with faster, leaving more time for product development or enhancement. Therefore the acceleration of coordination processes plays a significant role in providing high quality tenders.

The digitalization of relevant customer and manufacturer information, which is planned to be realized as a centralized web portal, should lead to time savings in dealing with service cases and maintenance and also simplifying the reuse of service related information. The consolidation of sales, service and engineering domains on the requirements management level ensures higher customer satisfaction in SME's. That is because the actual customers' needs can be better satisfied with individual specification and product functionality. Through the structured documentation of experience and knowledge from the product use phase, not only is an efficient quotation processing achieved, but the efficiency in product development can also be improved. It also enables the faster implementation of innovation. Overall, this approach minimizes product changes in higher product individuality and improves customer retention, which leads to a significant sales increase.

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Integration of Life Cycle Engineering and Multi-attribute Analysis to Support Product Development: Process Design and Material Selection for a Clothes Peg

C. Inácio, I. Ribeiro, P. Peças, and E. Henriques

Abstract Materials selection is one of the most important phases in the design of a product. In recent years there have been several methods to help designers in materials selection. Several factors such as the environmental impact of the products have been increasingly valued by the society in general, which has been a drive to include environmental analyses in materials selections methods. The recently arisen methodology Life Cycle Engineering provides just an answer to these needs. In this chapter the Life Cycle Engineering (LCE) methodology is applied to a simple case study – a clothes peg, within the objective of illustrate the potentialities of introducing LCE in early design phases. LCE is based on three dimensions of analysis: Life Cycle Cost, Life Cycle Assessment and a technical evaluation. Life Cycle Cost is an economic analysis of the product throughout its life. Life Cycle Assessment is an evaluation of environmental impacts caused during the product lifetime, and technical evaluation consists in the evaluation of the candidate materials based on the functions or the requirements of the product. The purpose of this study was to select candidate materials and to design the manufacturing process for a clothes peg applying the LCE methodology. The design alternatives were therefore evaluated based on these three dimensions of analysis. A decision making methodology called Multi-attribute Utility Analysis was used for the final selection of the best material and process. This analysis is based on the consumers' opinion, that in this particular application rely on three factors: the market price, the environmental impact and the quality of the product. The proposed methodology integrates a life cycle analysis (LCE) with the value given by the costumer to each dimension considering a specific product.

Keywords Life cycle engineering · Multi-attribute utility analysis · Materials selection · Process design

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1 Introduction

The selection of the material and most adequate production process are crucial phases in the course of product development. As material selection is part of product design and material decisions largely influence the product's costs and environmental impacts for its entire life cycle from the product manufacture to its disposal [1]. In this study the Life Cycle Engineering (LCE) methodology was used, aiming to compare and select the most appropriated material and manufacturing process. As foster by LCE the alternatives were compared for three different dimensions of analysis – economical, environmental and performance during its use. Moreover, the goal was also to evaluate the alternative's impacts throughout the product life cycle and to illustrate the need for an integrated analysis to estimate these impacts in an early design phase and support informed design decisions. In fact, unitary material cost, production costs and/or environmental impact may be insufficient as decision parameters.

Figure 1 illustrates the methodology and analysis tools used in this study. To apply this methodology a very simple case study was used: a clothes peg. The clothes peg design was considered fixed and the mechanical specifications were previously obtained by structural analysis and mechanical tests in laboratory. The next step was to select a set of candidate materials for the clothes peg using the computer software CES Edupack 2008, which is based on the Ashby's charts. These materials were selected according to the targeted specifications defined. In the following phase, these materials were compared by applying a method designated by "Materials Selection Engine", which is a structured method to verify the fulfilment level of the technical requirements for the materials previously selected for the product to identify a set of a few "potentially best" materials. Several simulations of the injection moulding process were then performed for the selected materials using the software Moldflow Plastics Insight. Additionally, several typologies of moulds for each material were also studied. The following

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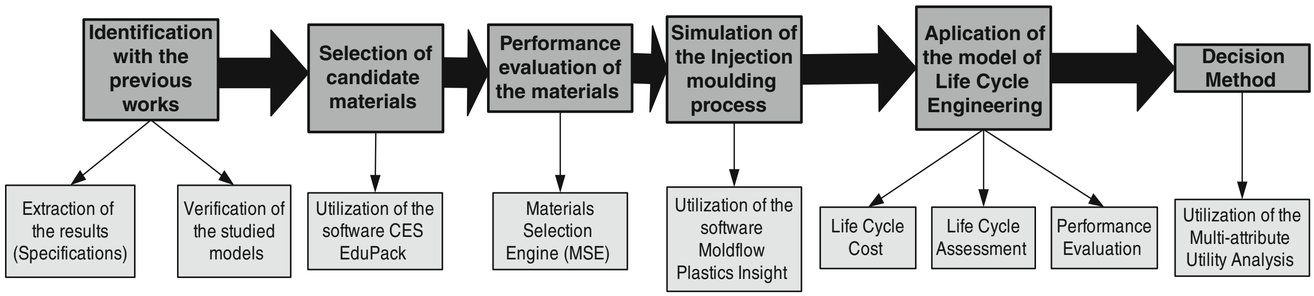

Fig. 1 Methodology used in the study

step consists in the application of the LCE methodology to these materials. Finally, the methodology Multi-attribute Utility Analysis was used to select the best material based on the studies of the LCE methodology. These methods are briefly explained in the following paragraphs.

2 Methods and Tools

In engineering design, material selection is carried out in several ways. There are many factors affecting material choice for a particular application such as cost, weight and manufacturability, to name only a few. Nevertheless, one of the initial selection criteria should be related with mechanical properties, since the candidate material must be fit-to-purpose [2]. Material properties charts are probably the most common and visual ways of selecting materials for a given application. This method allows for the selection of a material, or set of candidate materials, by comparing two engineering properties at a time [3].

In recent years due to the crescent concern of the environment aspects in the products life cycle, it was necessary to integrate them in the selection of materials. So, in response to that the LCE methodology has emerged [4].

The LCE methodology aims to develop life cycles causing the lowest possible environmental impacts, while still offering economic viability. LCE refers to "Engineering activities which include: the application of technological and scientific principles to the design and manufacture of products, with the goal of protecting the environment and conserving resources, while encouraging economic progress, keeping in mind the need for sustainability, and at the same time optimizing the product life cycle and minimizing pollution and waste" [5]. Therefore, LCE can be defined as a decision making methodology that considers performance, environmental, and cost dimensions throughout the duration of a product, guiding design engineers towards informed decisions [6, 7]. LCE differs from other life cycle methodologies in this point: while LCE incorporates these three dimensions of analysis, life cycle assessment (LCA) covers environmental aspects, life cycle cost (LCC) covers economic aspects and life cycle management (LCM) includes economic and environmental aspects [8]. Life cycle engineering includes not only conventional tools, as technical performance analysis based on mechanical, electrical, and chemical properties [9], but also life cycle tools to analyse economic performance (LCC) and environmental performance (LCA). LCC and LCA were chosen from a large number of available tools for their suitability for product assessment [10].

The LCC analysis can be described as a tool that translates the total costs introduced by the product, structure or system, during his life cycle. At the design level, the LCC main objective is to identify the economical consequences of a decision: for example in the material selection frequently the material with lower cost isn't economically viable at the end of life [11]. The LCA analysis is an environmental decision tool, which quantifies the environmental impact of a process or a product during his entire life [12]. The technical evaluation refers to material properties and their contribution to the technical requirements of the product [4].

The Multi-attribute Utility Analysis is a decision making method emerging as a powerful tool to identify the value of a material for a certain application, providing a way for materials selection and evaluation. Utility analysis affords a rational method of materials selection which avoids many of the fundamental logical difficulties of the alternative approaches. It is based on a series of inquiries to the customers/users in which they are asked to make choices under uncertainty to know what they most value in a product [13]. The method is suitable for this analysis as it allows evaluating several attributes and achieving a single score for each alternative regarding their performance in them. The axiomatic basis for measuring value by setting values in a probabilistic context was first set by Von Neumann and Morgenstern in 1947 [14]. According to Field and Neufille [14], "the utility of any characteristic is a measure of its value". The first step is then to define these attributes through interviews to the product users. After defining the relevant attributes, the second step is to define their utility to the customer/user through utility functions.

A utility function is a mapping of a multidimensional attribute space into a single-dimensioned preference space. It describes the measured value of several characteristics simultaneously, and its multidimensional surfaces, also called "multi-attribute" utility functions. The main advantage of this method is that it describes accurately the way people value characteristics and their relative preference [14, 15].

The most effective way to determine a person's utility towards a set of product attributes is to interview them directly through carefully designed questionnaires [16]. Finally, having defined the utility of a certain product regarding the selected attributes, it is possible to compare the performance of alternatives within this attribute space. This method, through the extension of the single-attribute utility functions to multiple dimensions allows, according to Clark, J et al, "to compare apples with oranges" [15].

3 Selection of Candidate Materials

In this section it is explained how the candidate materials were selected for the clothes peg presented in the Fig. 2. The selection started with the specifications for the clothes peg, through the study of the characteristics of similar current products in the market and a Value Analysis. This allows the definition of objective specifications for the clothes peg materials (Table 1).

In this phase, these specifications were entered in the software Ces Edupack 2008, which is based in the Ashby's materials selection charts [17], in order to determine which materials can meet them. There are two families of materials that meet these specifications: the woods and the polymers. However, it was decided to exclude the woods in this study because the manufacturing process involved in producing this product in wood is very different than the one used for polymers and it is not dominated by the industrial company sponsoring the study. So, in the polymers families 7 different materials were selected. Table 2 presents the values of the main mechanical properties for each material. It is possible to notice that there are materials with mechanical properties closer to the clothes peg material specifications. For example, PP, PS and ABS have their properties closer to the specifications than PVC, PET, POM and PMMA. In terms of the material price, the differences are not huge, but still are possible to identify PVC, PET and PS as the materials with the lowest cost when compared to the others.

Table 1 Specifications for the clothes peg

1st Specification	2nd Specification	3rd Specification
Density (Kg/m^3)	Yield strength (MPa)	Young's modulus (GPa)
1500	30	1
Maximum value	Minimum value	Minimum value

4 Analysis of the Materials Performance

The objective of this analysis was to determine the materials that best meet the specifications and eliminate those that aren't suitable for the product. For these the procedure proposed within the Materials Selection Engine [3] was followed. The first step is the identification, through a detailed analysis of the product, of the functions that it must comply. In the present case the identified function were: "Hold the clothes", "Be economic", "Be comfortable", "Be robust" and "Be durable".

The second step consists in classifying the functions according to their importance. This was made by a pair wise analysis. It was verified that the requirements "Hold the clothes" and "Be economic" were the most important since the first is the primary one as regards the product objective and the second is crucial for the product acceptance in the market. The most important properties that are directly related to the functions of the clothes pegs were then identified: yield strength, Young's modulus, price of material, resistance to water and UV light. A classification linking each mechanical/physical property to each function is then assigned to determine the relative importance (or weight) of each property. In other words, the method attributes a score to the mechanical properties according to their importance to

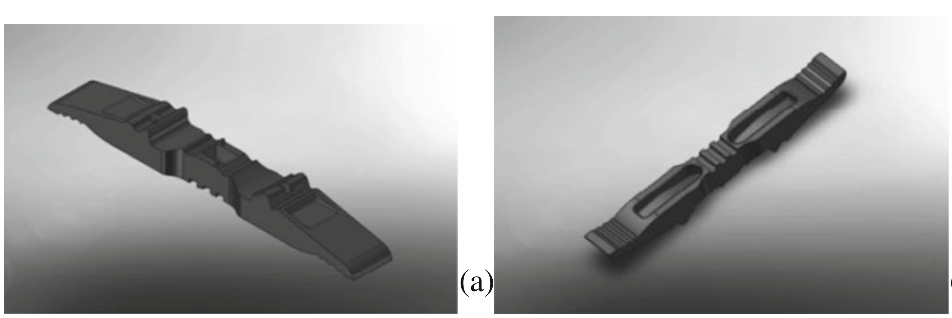
(a) (b)

Fig. 2 (**a**) and (**b**): CAD model of the clothes peg. (Patents nº PT103874, PT1012, PT1013)

Table 2 Properties of the selected materials

Polymers	Density (Kg/m^3)	Young's modulus (GPa)	Yield strength (MPa)	Price (€/Kg)
PVC	1300–1580	2.14–4.14	35.4–52.1	1.04–1.14
PET	1290–1400	2.76–4.14	56.5–62.3	1.11–1.22
PS	1040–1050	1.20–2.60	28.7–56.2	1.23–1.36
PP	890–910	0.896–1.55	20.7–37.2	1.45–1.6
POM	1390–1430	2.5–5	48.6–72.4	1.55–1.7
ABS	1010–1210	1.1–2.9	18.5–51	1.59–1.74
PMMA	1160–1220	2.24–3.8	53.8–72.4	1.67–1.84

Table 3 Ranking of the materials

Mech. Prop.	Mech. Prop. weight		PP (PP 1052)	PS (Empera 416)	ABS (Novodur P2K)	PVC (HH – 1900)	PMMA (Delpet SR8500)	POM (Ultraform N2640 Z6 UNC)	PET (Rynite 415 HP NC 010)
		Value (Mpa)	33.00	30.00	34.00	41.40	30.00	37.00	79.00
Yield Strength	36.1	Adimensional	0.90	0.99	0.88	0.72	0.99	0.81	0.38
		Score	32.66	35.93	31.70	26.03	35.93	29.13	13.64
		Value (Gpa)	1.50	2.60	1.70	2.48	1.30	1.30	4.22
Young's modulus	26.0	Adimensional	0.67	0.38	0.59	0.40	0.77	0.77	0.24
		Score	17.34	10.01	15.30	10.49	20.01	20.01	6.16
		Value (€/Kg)	0.80	0.90	1.15	1.10	2.10	1.40	1.20
Material price	35.8	Adimensional	1.00	0.89	0.70	0.73	0.38	0.57	0.67
		Score	35.84	31.86	24.93	26.07	13.65	20.48	23.89
		Value	2.00	3.00	3.00	5.00	5.00	2.00	4.00
Resist. to UV	1.6	Adimensional	0.40	0.60	0.60	1.00	1.00	0.40	0.80
		Score	0.64	0.96	0.96	1.60	1.60	0.64	1.28
		Value	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Resist. to water	0.4	Adimensional	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Score	0.40	0.40	0.40	0.40	0.40	0.40	0.40
		Weight material index	86.89	79.15	73.30	64.59	71.59	70.66	45.38
		Ranking	1st	2nd	3rd	6th	4th	5th	7th

the respective function. The scores given were in the ranges of 1–10 to each property. In the second column of Table 3 the weight of each mechanical property is present. One can notice that the yield strength is the most important property, and the price of the material is the second. The Youngś modulus, the resistance to UV light and to the water have a minor importance, in comparison with the other properties.

The next step was to select a specific material for each polymer's family (top row of Table 3). The criterion was to choose the materials that are closer to the specifications of the clothes peg presented in the Table 1. For each material the values of their mechanical properties are adimensionalized using the initial specification target value. Finally, the adimensional values are multiplied by the mechanical property weight. The sum of the values of all mechanical properties gives the weight material index, as presented in Table 3.

This analysis shows that the material with a higher ranking is PP followed by the PS, ABS, PMMA and POM. The materials PVC and PET were decided to be excluded, due to its low scores.

5 Analysis of the Injection Moulding Process

The type of product and the selected materials (polymers) make easy the selection of the manufacturing process. In fact, injection moulding is the most appropriate process to obtain sound polymer parts in high quantities (as required for a clothes peg). So the process design in this study in mainly dedicated to the selection of the proper injection moulding parameters, namely the mould dimensions and injection process.

This section describes the procedure used in the simulation of the injection moulding process, using the software Moldflow Plastics Insight. This software enables a complete simulation of the process from the design of the runner and the cooling systems to the estimation of the main parameters of the process, such as cycle time, maximum injection pressure, clamp force and maximum flow rate.

5.1 Process Parameters

In this section the analysis of the process parameters is explained. It can be divided into four main studies: mould typologies, materials processing conditions, mould materials and injection machine.

Four different mould typologies for each candidate material were analysed, which differ in terms of the number of cavities (32 and 96) and runner system (cold – Q- and hot runners -F), totalizing 20 alternatives.

The main parameters considered for the materials processing conditions were the temperature of the mould, the melt temperature and the injection temperature.

As regards to the moulds material, two materials were selected to meet a compatible duration with the total production volume. To accommodate 1,000,000 injection cycles and depending on the injection material – the AISI H13 for PS, ABS and PMMA and the AISI Type 420 for PP and POM were considered for mould materials.

Finally, regarding the injection machine, a standard injection machine was used for a preliminary analysis suing the simulation software. However, one of the objectives of the simulation of the injection process is to select the best injection machine for each alternative. So when the main parameters were determined, the best injection machine was selected for each alternative.

5.2 Simulation of the Injection Process

In this section all the steps taken to the simulation of the injection process are explained. The procedure is divided in 6 steps: generation of the mesh, the injection point location, the cavities layout, the design of the runner system, the design of the cooling system and mould open time.

For the generation of the mesh for the model a fusion mesh was chosen and the software generates it automatically. Next, an analysis of the mesh was made to detect potential mesh inaccuracies, which need manual correction. Note that mesh shouldn't be highly refined because this would increase slightly the computation time, in a way that might not be compatible with a procedure for material selection in a design phase.

The second step consisted in selecting the best injection point location. It was verified that the best location is in the edge of the part, to reduce the associated non-quality surface generated.

The third and the fourth step were performed together, because are dependent on each other. To make these steps a filling analysis was necessary to verify if all the cavities are properly filled. It was decided to use cylindrical runners. The dimensions of the runners are different according to the number of cavities, but there is no change according to the injection material. One fact that was taken into consideration was that in the case of the cold runners they are extracted with the parts. So in these cases the dimensions of the runners are the smaller possible. The only exception was with the diameter of the attack orifice, which depends on the injection material.

Regarding the cooling system several typologies were tested to determine the one that provides a more efficient (quicker) cooling of the mould and the part.

Finally, for the mould's open time, the necessary time to extract the parts from the mould cavities was estimated with the support of the company which is currently producing the clothes pegs.

5.3 Results

Besides the process capability, the main result of the simulation is the cycle time. The cycle time for the different alternatives is represented in Fig. 3. Other results, as the injection pressure, the maximum flow rate and the clamp force are also important but mainly for the selection of the injection machine, so they are not presented here.

The analysis showed that the injection material POM is the one with the lowest cycle time among all alternatives. Relating with the typology of the mould, the one with the lowest cycle time is the typology with 32 cavities and hot runners.

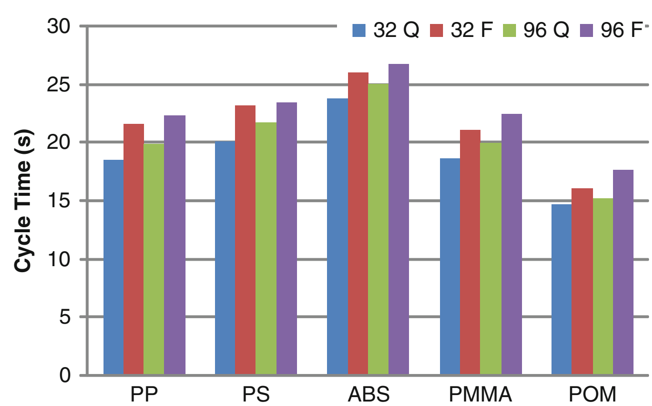

Fig. 3 Cycle times (in seconds) for the candidate materials and mould type alternatives (32Q & 96Q: 32 and 96 cavity mould with hot-runners; (32F & 96F: 32 and 96 cavity mould with cold-runners)

6 Application of the LCE Methodology

The LCE methodology is divided in three different analyses: Life Cycle Cost, Life Cycle Assessment and technical performance evaluation.

6.1 Life Cycle Cost

The model used in this study is represented in Fig. 4. This analysis was based on the "Process-based Cost Model", which, considering the process, operational and economical framework, has the main advantage of making easy any sensitivity analysis and parameters modification [18].

Two main costs were considered – the input cost related with the injection material and the cost of the mould, and the process costs that are related with the costs of the injection system and the shredder machines. Note that it was considered that the shredded material is reused.

As regards to the cost of the injection material a polymer supplier was contacted. In order to outline the cost of the moulds in the several alternatives, mould makers was inquired and quotations were asked. The process costs were based on hourly cost of non-dedicated machines, which depends on their acquisition cost, number of days and hours that the machine is working, opportunity cost and the equipment life. The injection machine was selected for each mould typology, taking in account the parameters obtained in simulation of the injection process and the dimension of the mould.

Additionally, the estimation of the amount of energy and the labour to produce the product was also computed, considering a production volume of 2,400,000 clothes pegs per year.

Taking in consideration all these factors it was obtained the total costs for the total production volume. In Fig. 5 the total costs are compared for each alternative. Finally, this study shows that the option that incur in the lowest cost is the one with a mould of 32 cavities with cold runners for the injection material PP.

6.2 Life Cycle Assessment

The model used in the Life Cycle Assessment is represented in the Fig. 6.

This analysis was divided in three stages: the production of the materials, the injection moulding process and the end of life. For this analysis the Eco Indicator 99 was considered and its values were obtained through the software application SimaPro 7.1.

For the first stage the amount of injection material necessary was estimated for the annual production volume of 2,400,000 clothes pegs. For the mould it was also estimated the weight of the mould. Note that, in this study the production of the mould isn't considered. Only the environmental impact of the production of the mould material is accounted. In fact, as stated by Peças et al. [19], the environmental impact of the consumed energy and consumables materials in the mould production phase is negligible when compared with the ones required for the production phase of the mould raw material.

The second stage consists in estimating the amount of energy required for the injection and shredder machines.

In the third stage it is considered that at the end of the moulds life, the steel is recycled and at the end of product life, the clothes pegs plastic material goes to a landfill.

Figure 7 represents the global environmental impacts achieved. This analysis shows highlights the PP materials as the material that causes a lower environmental impact.

6.3 Technical Evaluation

For this study a similar methodology to the one exposed in the Sect. 4 was applied. However, here the function "Be economic" was removed because the objective is now to

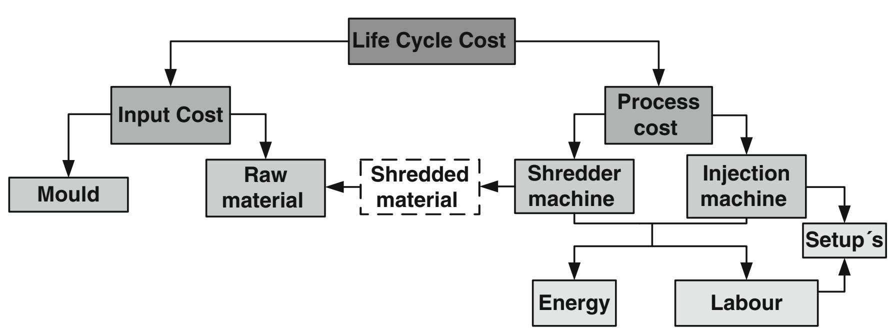

Fig. 4 Methodology applied in the life cycle cost

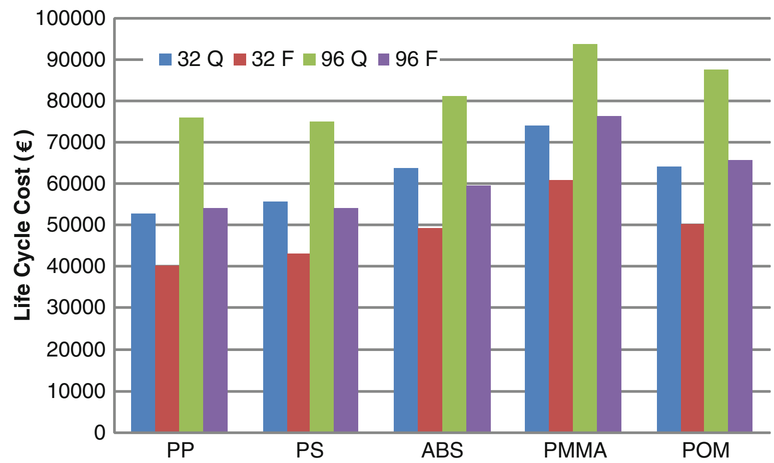

Fig. 5 Total costs for each alternative. (32Q & 96Q: 32 & 96 cavity mould with hot-runners; (32F & 96F: 32 & 96 cavity mould with cold-runners)

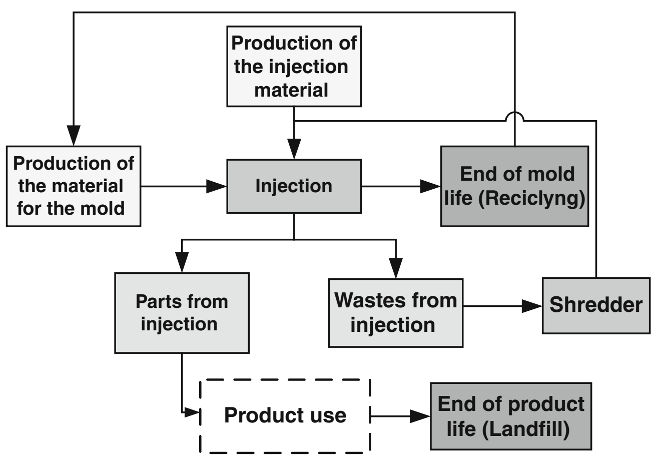

Fig. 6 Model applied in the LCA

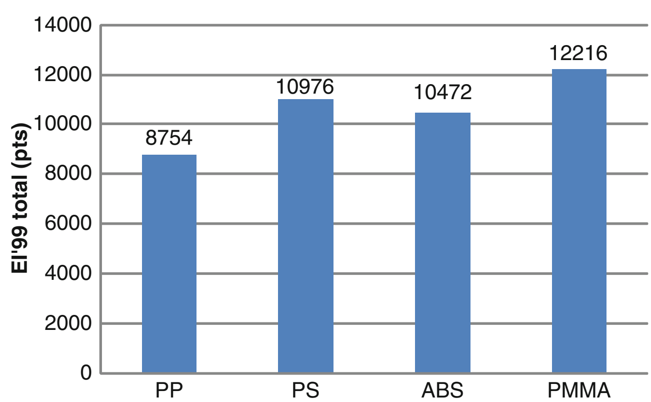

Fig. 7 Global environmental impacts

determine the best material for this application from the point of view of the technical performance of the product. The target value to the determination of the adimensional value was also changed. It was considered the higher value of each property. In Table 4 the ranking of the alternatives is presented. Results show that the clothes peg made of PS has the highest score.

7 Decision-Making Methodology – Multi-Attribute Utility Analysis

Finally, a methodology to help in the decision of choosing the best material for the clothes pegs was used – the Multi-attribute Utility Analysis, that is based in a series of questionnaires to the customers/users. The objective of the questionnaire is to know what the customers/users value the most in a clothes peg, in a spectrum of three attributes: the market price of the clothes peg, the environmental impact and the technical evaluation (in this point this attribute will be called quality). This value is obtained through utility functions, being a utility function the mapping of a multi-dimensional attribute space into a single dimensioned preference space. Based upon repeated evaluations of carefully constructed decision problems (through questionnaires), an analyst can define a mathematical mapping of this performance space into a single dimension of preference, which establishes an ordering to all points in the attribute space. These utility functions are classified as von Neumann-Morgenstern utility functions, characterized by the fact that they are consistent under probabilistic expectation, i.e. if an individual is indifferent between a given alternative A, and a situation in which there is a probability p that alternative B will obtain and a probability $(1–p)$ that alternative C will obtain, then $U(A) = pU(B) + (1 - p)U(C)$. In this case, the alternatives refer to levels of market price, quality and environmental impacts of the clothes pegs.

This characteristic of von Neumann-Morgenstern utility yields a powerful ability; utility functions of this form can be successively approximated through repeated inquiries under

Table 4 Ranking of the clothes pegs made of different materials

Mechanical properties	Mechanical properties weight		PP	PS	ABS	PMMA	POM
Yield Strength	54.90	Value (Mpa)	33	30	34	30	37
		Adimensional	0.89	0.81	0.92	0.81	1.00
		Score	48.96	44.51	50.45	44.51	54.90
Young's Modulus	43.10	Value (Gpa)	1.50	2.60	1.70	1.30	1.30
		Adimensional	0.58	1.00	0.65	0.50	0.50
		Score	24.87	43.10	28.18	21.55	21.55
Resist. to UV	1.60	Value ()	2	3	3	5	2
		Adimensional	0.40	0.60	0.60	1.00	0.40
		Score	0.64	0.96	0.96	1.6	0.64
Resist. to water	0.40	Value ()	5	5	5	5	5
		Adimensional	1	1	1	1	1
		Score	0.40	0.40	0.40	0.40	0.40
Weight material index			74.87	88.97	79.99	68.06	77.49
	Ranking		4th	1st	2nd	5th	3rd

which individuals are asked to make choices under uncertainty. Such a utility function, limited only by the subject's patience and the questioner's persistence, can be used to predict the subject's choice in any situation falling within the domain of the measured space.

In this case study, the subjects questioned were the clothes pegs users, and the selection of these attributes was based in the studies of the LCE. After analyzing the results of the questionnaires, the final results were build-up and they are presented in Fig. 8. The graph represents the utility in function of the market price of the clothes pegs made of the different materials. The points represent the utility of each alternative under analysis for a mark-up based on 75% of the clothes peg price and for the production costs calculated in Sect. 5.1. (price = mark-up + production cost)

From the chart it is visible that the PS' utility function allows for higher utility for the same market price – for the same market price the customers/users perceive a higher benefit (environmental impacts and quality) on the clothes pegs made of PS. Nevertheless, for this particular application, the production cost of PP clothes pegs is lower than the production cost of the PS ones, resulting in similar differences as regards their market price. The result is an equivalent specific utility of the clothes pegs made of the two materials. The decision maker is then well supported to make an informed decision. The company sponsoring the study selected the clothes pegs made of PP as the best alternative to launch in the market, based on an empirical reasoning that privileged the lower market price.

Another analysis was made (Fig. 9) in which the environmental impact was more valuated than the quality. In these conditions the PP is the best material, due to its higher utility value.

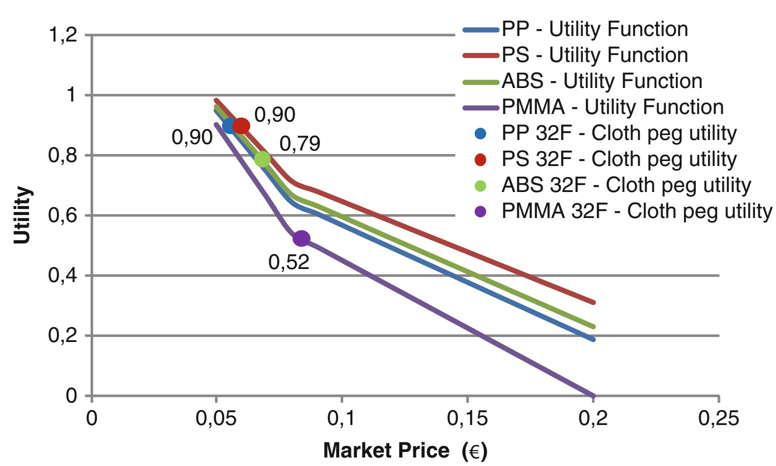

Fig. 8 Utility vs. market price

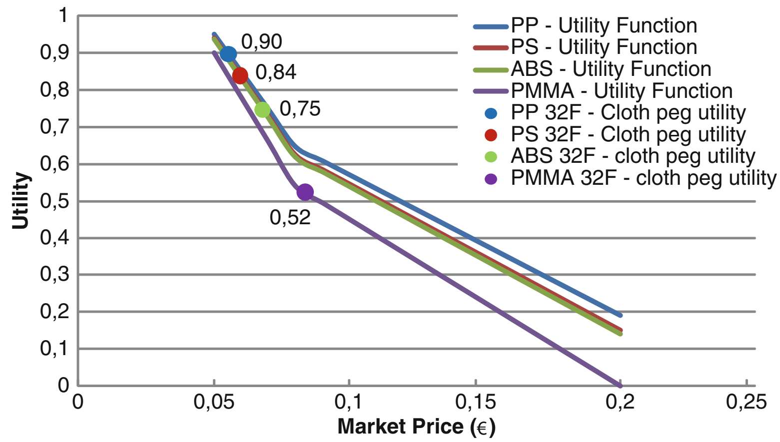

Fig. 9 Utility vs. market price, giving more importance to the attribute "environmental impact"

8 Summary

In this chapter the LCE methodology was applied to show how a comprehensive method that includes not only cost but also performance and environmental impacts can help designers in the design stage of a product. Moreover, these analyses weren't focused only on initial costs or environmental aspects, but aimed to compute the design decision impacts throughout the product life cycle. In this study a very simple product was chosen to exemplify the usefulness of this type of analyses – a clothes peg. This methodology encompasses three different dimensions; an economical study, an environmental study and a technical evaluation of product. This enables a complete study of the most important considerations for the materials selection. Moreover, when a decision tool as Multi Attribute Utility Analysis is used, the results obtained through the above comprehensive analysis can be integrated in a single framework, considering the value given by the customers/users to the different dimensions of analysis.

Regarding this particular case, the results showed that there are two materials that are with no doubt the best choices for this product, which are the PP and the PS, as they showed to be the best materials in the analysis performed with the LCE methodology. Through the utility analysis, it was concluded that the best material from costumers/users point of view is the PP.

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Multiobjective Design Optimization of 3–PRR Planar Parallel Manipulators

S. Caro, D. Chablat, R. Ur-Rehman, and P. Wenger

Abstract This chapter addresses the dimensional synthesis of parallel kinematics machines. A multiobjective optimization problem is proposed in order to determine optimum structural and geometric parameters of parallel manipulators. The proposed approach is applied to the optimum design of a three-degree-of-freedom planar parallel manipulator in order to minimize the mass of the mechanism in motion and to maximize its regular shaped workspace.

Keywords Parallel manipulators · Workspace · Design · Multiobjective optimization

1 Introduction

The design of parallel kinematics machines is a complex subject. The fundamental problem is that their performance heavily depends on their geometry [1] and the mutual dependency of almost all the performance measures. This makes the problem computationally complex and yields the traditional solution approaches inefficient. As reported in [2], since the performance of a parallel manipulator depends on its dimensions, the latter depend on the manipulator application(s). Furthermore, numerous design aspects contribute to the Parallel Kinematics Machine (PKM) performance and an efficient design will be one that takes into account all or most of these design aspects. This is an iterative process and an efficient design re quires a lot of computational efforts and capabilities for mapping design parameters into design criteria, and hence turning out with a multiobjective design optimization problem. Indeed, the optimal geometric parameters of a PKM can be determined by means of a the resolution of a multiobjective optimization problem. The solutions of such a problem are non dominated solutions, also called Pareto-optimal solutions. Therefore, design optimization of parallel mechanisms is a key issue for their development.

Several researchers have focused on the optimization problem of parallel mechanisms the last few years. They have come up either with mono- or multi-objective design optimization problems. For instance, Lou et al. presented a general approach for the optimal design of parallel manipulators to maximize the volume of an effective regular-shaped workspace while subject to constraints on their dexterity [3, 4]. Hay and Snyman [1] considered the optimal design of parallel manipulators to obtain a prescribed workspace, whereas Ottaviano and Ceccarelli [5, 6] proposed a formulation for the optimum design of 3-Degree-Of-Freedom (DOF) spatial parallel manipulators for given position and orientation workspaces. They based their study on the static analysis and the singularity loci of a manipulator in order to optimize the geometric design of the Tsai manipulator for a given free from singularity workspace.

Hao and Merlet [7] discussed a multi-criterion optimal design methodology based on interval analysis to determine the possible geometric parameters satisfying two compulsory requirements of the workspace and accuracy. Similarly, Ceccarelli et al. [8] dealt with the multi-criterion optimum design of both parallel and serial manipulators with the focus on the workspace aspects, singularity and stiffness properties. Gosselin and Angeles [9, 10] analyzed the design of a 3-DOF planar and a 3-DOF spherical parallel manipulators by maximizing their workspace volume while paying attention to their dexterity. Pham and Chen [11] suggested maximizing the workspace of a parallel flexure mechanism with the constraints on a global and uniformity measure of manipulability. Stamper et al. [12] used the global conditioning index based on the integral of the inverse condition number of the kinematic Jacobian matrix over the workspace in order to optimize a spatial 3-DOF translational parallel manipulator. Stock and Miller [13] formulated a weighted sum multi-criterion optimization problem with manipulability

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and workspace as two objective functions. Menon et al. [14] used the maximization of the first natural frequency as an objective function for the geometrical optimization of the parallel mechanisms. Similarly, Li et al. [15] proposed dynamic and elastodynamic optimization of a two-DOF planar parallel robot to improve the dynamic accuracy of the mechanism. They proposed a dynamic index to identify the range of natural frequency with different configurations. Krefft [16] also formulated a multi-criterion elastodynamic optimization problem for parallel mechanisms while considering workspace, velocity transmission, inertia, stiffness and the first natural frequency as optimization objectives. Chablat and Wenger [17] proposed an analytical approach for the architectural optimization of a 3-DOF translational parallel mechanism, named Orthoglide 3-axis, based on prescribed kinetostatic performance to be satisfied in a given Cartesian workspace. Most of the foregoing research works aimed to improve the mechanisms' performance throughout their whole workspace. In this chapter, the mechanisms' performance are improved over a regular shaped workspace that is defined based on the specifications. As a result, we propose a methodology to deal with the multiobjective design optimization of PKMs. The size of the regular shaped workspace and the mass in motion of the mechanism are the objective functions of the optimization problem. Its constraints are determined based on the mechanism accuracy, assembly and the conditioning number of its kinematic Jacobian matrix. The proposed approach is highlighted with the optimal design of a 3-DOF Planar Parallel Manipulator (PPM). The non-dominated solutions, also called Pareto-optimal solutions, are obtained by means of a genetic algorithm.

2 3-PRR Planar Parallel Manipulators

Planar parallel manipulators are distinguished by the fact that all their components and corresponding motions, including their end-effector, generate planar motions. Their architecture is simple and they are usually simple to control. They can find many applications in planar motions that require high dynamics. Their weakness is their difficulty to carry out a large payload whose the weight is normal to the plane of motion. 3-DOF PPMs are classified in families, namely, the 3–RRR, 3–RPR, 3–PRR and 3–PPP PPMs where R and P stand for revolute and prismatic joints, respectively. Those families are described in [2]. In the scope of this chapter, we focus on the optimum design of 3–PPP PPMs, where P denotes an actuated prismatic joint. However, the proposed approach can be applied to any type of PPM.

2.1 Manipulator Architecture

A 3-DOF PPM with three identical chains is shown in Fig. 1. Each kinematic chain is of PRR-type and consists of one

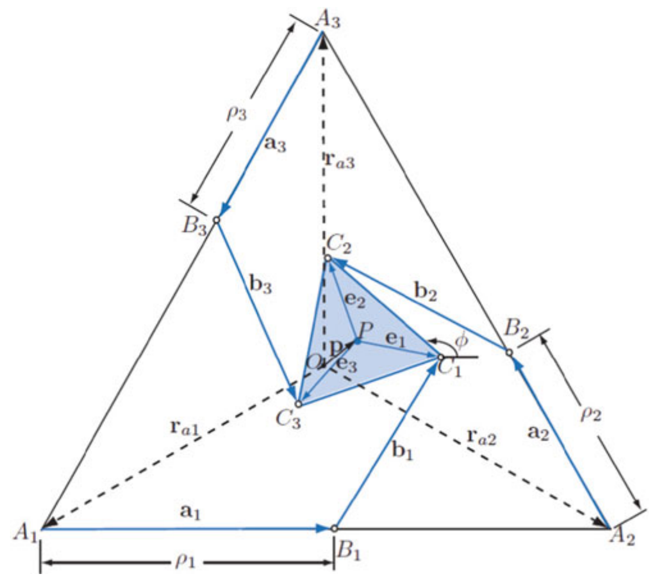

Fig. 1 3–PRR planar parallel manipulator

actuated prismatic joint, P; two revolute joints, R; and two links. This 3-PRR manipulator is intended to position and orient the equilateral triangle-shaped platform $C_1C_2C_3$ in the plane of motion. The geometric center of platform $C_1C_2C_3$, denoted by P, is the operation point of the manipulator. The displacements of the three prismatic joints, i.e., ρ_1, ρ_2 and ρ_3, are the input variables whereas the Cartesian coordinates of point P, i.e., x_p and y_p, and the orientation of the platform are the output variables. The base-platform of the manipulator is also an equilateral triangle with vertices A_1, A_2 and A_3, point O is its geometric center and the origin of the reference frame. The prismatic actuators are aligned to its sides and are attached to points $A_i (i = 1, 2, 3)$ with orientation angles α_1, α_2, and α_3 being equal to 0, 120 and 240°, respectively. Here are the parameters describing the manipulator geometry:

- R: radius of the circumscribed circle of triangle $A_1A_2A_3$ of center O, i.e., $R = OA_i$;
- r: radius of the circumscribed circle of triangle $C_1C_2C_3$ of center P, i.e., $r = PC_i$;
- L_b: the length of the intermediate links, i.e., $L_b = B_iC_i$;
- r_j: the cross-section radius of the intermediate link;
- r_p: the cross-section radius of the moving platform link

2.2 Kinematic Modelling of the 3-PRR PPM

Knowing the geometric parameters of the mechanism, i.e., R, r and L_b, its Inverse Kinematics Model (IKM) gives the relation between the actuators displacements ρ_1, ρ_2 and ρ_3 and the moving platform pose, i.e., x_p, y_p and ϕ:

$$\rho = f(x_{\mathrm{p}}) \tag{1}$$

with

$$\rho = [\,\rho_1\ \rho_2\ \rho_3\,]^{\mathrm{T}} \tag{2a}$$

$$x_{\mathrm{p}} = [\,x_{\mathrm{p}}\ y_{\mathrm{p}}\ \phi\,]^{\mathrm{T}} \tag{2b}$$

Equation (1) can be expressed as a quadratic equation [18]. The latter may have eight solutions corresponding to the eight working modes of the mechanism [19]. The choice of the working mode can also be used as a design parameter of the mechanism as it modifies the location of its singular configurations. The Direct Kinematics Model (DKM) of the manipulator characterizes the moving platform pose in terms of the prismatic actuators displacements:

$$x_{\mathrm{p}} = f(\rho) \tag{3}$$

The DKM of the 3−PRR PPM may have six solutions corresponding to the six assembly modes of the mechanism [20].

2.3 Kinematic Jacobian Matrix of the 3-PRR PPM

The kinematic Jacobian matrix defines the relationship between the actuators and mobile platform velocity vectors. For the ith kinematic chain, a closed loop vector equation can be written as:

$$\overrightarrow{OP} = \overrightarrow{OA_i} + \overrightarrow{A_iB_i} + \overrightarrow{B_iC_i} + \overrightarrow{C_iP} \tag{4}$$

Equation (4) can be expressed algebraically as:

$$\mathrm{p} = R\mathrm{r}_{ai} + \rho_i \mathrm{a}_i + L_b \mathrm{b}_i - r\mathrm{e}_i \tag{5}$$

with $\mathbf{a}_i$, $\mathbf{b}_i$, $\mathbf{e}_i$ and $\mathbf{r}_{ai}$ being the unit vectors depicted in Fig. 1. Upon differentiation of Eq. (5) with respect to time we get,

$$\dot{\mathrm{p}} = \dot{\rho}_i \mathrm{a}_i + L_b \dot{\mathrm{b}}_i - r\dot{\mathrm{e}}_i \tag{6}$$

$\dot{\mathbf{b}}_i$ and $\dot{\mathbf{e}}_i$ being written as:

$$\dot{\mathrm{b}}_i = \dot{\beta}_i \mathrm{E}\mathrm{b}_i \qquad \dot{\mathrm{e}}_i = \dot{\phi}\mathrm{E}\mathrm{e}_i \tag{7}$$

$\dot{\beta}_i$ is the angular velocity of the ith intermediate link and $\mathbf{E}$ is the right angle rotation matrix given by:

$$\mathrm{E} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \tag{8}$$

Accordingly, Eq. (6) becomes

$$\dot{\mathrm{p}} = \dot{\rho}_i \mathrm{a}_i + L_b \dot{\beta}_i \mathrm{E}\mathrm{b}_i - r\dot{\phi}\mathrm{E}\mathrm{e}_i \tag{9}$$

Upon multiplication of Eq. (9) by $\mathbf{b}_i^{\mathrm{T}}$, we obtain the matrix form:

$$\mathrm{A}\dot{\mathrm{x}}_p = \mathrm{B}\dot{\rho} \tag{10}$$

with

$$\mathrm{A} = \begin{bmatrix} b_1^{\mathrm{T}} & rb_1^{\mathrm{T}}\mathrm{E}\mathrm{e}_1 \\ b_2^{\mathrm{T}} & rb_2^{\mathrm{T}}\mathrm{E}\mathrm{e}_2 \\ b_3^{\mathrm{T}} & rb_3^{\mathrm{T}}\mathrm{E}\mathrm{e}_3 \end{bmatrix} \tag{11}$$

and

$$\mathrm{B} = \begin{bmatrix} b_1^{\mathrm{T}}\mathrm{a}_1 & 0 & 0 \\ 0 & b_2^{\mathrm{T}}\mathrm{a}_2 & 0 \\ 0 & 0 & b_3^{\mathrm{T}}\mathrm{a}_3 \end{bmatrix} \tag{12}$$

Therefore, the prismatic joint rates are expressed in terms of the moving platform twist as follows:

$$\dot{\rho} = \mathrm{B}^{-1}\mathrm{A}\dot{\mathrm{x}}_p = \mathrm{J}\dot{\mathrm{x}}_p \tag{13}$$

where $\mathbf{J}$ is the kinematic Jacobian matrix of the manipulator.

$$\mathrm{J} = \mathrm{B}^{-1}\mathrm{A} = \frac{1}{\mathrm{a}_i, \mathrm{b}_i} \begin{bmatrix} \mathrm{b}_1 & rk\ (\mathrm{b}_1 \times \mathrm{e}_1) \\ \mathrm{b}_2 & rk\ (\mathrm{b}_2 \times \mathrm{e}_2) \\ \mathrm{b}_3 & rk\ (\mathrm{b}_3 \times \mathrm{e}_3) \end{bmatrix} \tag{14}$$

The singular configurations of the 3–PRR PPM can be obtained by means of a singularity analysis of $\mathbf{J}$ as explained in [18].

2.4 Stiffness Matrix

The stiffness model of the 3-PRR PPM is obtained by means of the refined lumped mass modeling presented in [21]. Let us consider a general schematic of the 3-PRRPPM that is composed of a mobile platform connected to a fixed base by means of three identical kinematics chains, as shown in Fig. 2. Each kinematic chain contains an actuated prismatic joint and two passive revolute joints.

According to the flexible model described in [21], each kinematic chain of the 3-PRR manipulator can be considered as a serial architecture as shown in Fig. 3 that contains sequentially:

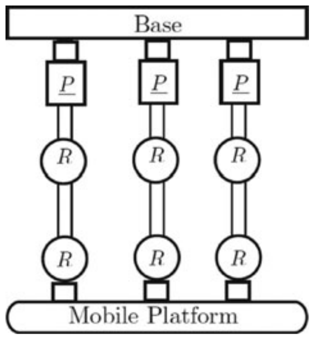

Fig. 2 Schematic diagram of a 3-PRR

- a rigid link between the manipulator base and the ith actuated joint (part of the base platform) described by the constant homogeneous transformation matrix $\mathbf{T}^i_{\text{Base}}$;
- a 1-dof actuated joint, defined by the homogeneous matrix function $\mathbf{V}_a(q^i_0)$ where q^i_0 is the actuated coordinate;
- a 1-dof virtual spring describing the actuator mechanical stiffness, which is defined by the homogeneous matrix function $\mathbf{V}_{s_1}(\theta^i_0)$ where θ^i_0 is the virtual spring coordinate corresponding to the translational spring;
- a 1-dof passive R joint at the beginning of the leg allowing one rotation angle q^i_2, which is described by the homogeneous matrix function $\mathbf{V}_{r_1}(q^i_2)$;
- a rigid leg of length L linking the foot and the movable platform, which is described by the constant homogeneous transformation matrix$\mathbf{T}^i_L$;
- a 6-dof virtual spring describing the leg stiffness, which is defined by the homogeneous matrix function $\mathbf{V}_{s_2}(\theta^i_1 \ldots \theta^i_6)$ with $\theta^i_1, \theta^i_2, \theta^i_3$ and $\theta^i_4, \theta^i_5, \theta^i_6$ being the virtual spring coordinates corresponding to the spring translational and rotational deflections;
- a 1-dof passive R-joint between the leg and the platform, allowing one rotation angle q^i_3, which is described by the homogeneous matrix function $\mathbf{V}_{r_2}(q^i_3)$;
- a rigid link of length r from the manipulator leg to the centroïd of the mobile platform, which is described by the constant homogeneous transformation matrix $\mathbf{T}^i_r$;
- a 6-dof virtual spring describing the stiffness of the moving platform, which is defined by the homogeneous matrix function $\mathbf{V}_{s_3}(\theta^i_7 \ldots \theta^i_{12})$, $\theta^i_7, \theta^i_8, \theta^i_9$ and $\theta^i_{10}, \theta^i_{11}, \theta^i_{12}$ being the virtual spring coordinates corresponding to translational and rotational deflections of link C_iP;
- a homogeneous transformation matrix $\mathbf{T}^i_{\text{End}}$ characterizing the rotation from the 6-dof spring associated with link C_iP and the manipulator base frame.

The corresponding mathematical expression defining the end-effector location subject to variations in all above defined coordinates of the ith kinematic chain can be written as follows:

$$\begin{aligned} \mathrm{T}^i = {} & \mathrm{T}^i_{\text{Base}} \mathrm{V}^i_\alpha(q^i_0) \mathrm{V}_{s1}(\theta^i_0) \mathrm{V}_{r1}(q^i_1) \mathrm{T}^i_L \mathrm{V}_{s2} \\ & (\theta^i_1 \cdots \theta^i_6) \mathrm{V}_{r2}(q^i_2) \mathrm{T}^i_r \mathrm{V}_{s3}(\theta^t_7 \cdots \theta^t_{12}) \mathrm{T}^i_{\text{Base}} \end{aligned} \tag{15}$$

From [21], the kinetostatic model of the ith leg of the 3-PRR PPM can be reduced to a system of two matrix equations, namely,

$$\begin{bmatrix} \mathrm{S}^i_\theta & \mathrm{J}^i_q \\ \mathrm{J}^i_q & 0_{2\times 2} \end{bmatrix} \begin{bmatrix} \mathrm{f}_i \\ \delta \mathrm{q}_i \end{bmatrix} = \begin{bmatrix} \delta \mathrm{t}_i \\ 0_2 \end{bmatrix} \tag{16}$$

where the sub-matrix $\mathbf{S}^i_\theta = \mathbf{J}^i_\theta \mathbf{K}^{i-1}_\theta \mathbf{J}^{i\mathrm{T}}_\theta$ describes the spring compliance relative to the centroid of the moving platform, and the sub-matrix $\mathbf{J}^i_q$ takes into account the passive joint influence on the moving platform motions.

$\mathbf{K}^{i-1}_\theta$matrix, of size 13×13, describes the compliance of the virtual springs and takes the form:

$$\mathrm{K}^{i-1}_\theta = \begin{bmatrix} \mathrm{K}^{i-1}_{\text{act}} & 0_{1\times 6} & 0_{1\times 6} \\ 0_{6\times 1} & \mathrm{K}^{i-1}_{\text{leg}} & 0_{6\times 6} \\ 0_{6\times 1} & 0_{6\times 6} & \mathrm{K}^i_{\text{pf}} \end{bmatrix} \tag{17}$$

where $\mathbf{K}^i_{\text{act}}$ is the 1×1 stiffness matrix of the ith actuator, $\mathbf{K}^i_{\text{leg}}$ is the 6×6 stiffness matrix of the ith intermediate leg and $\mathbf{K}^i_{\text{pf}}$ is the 6×6 the stiffness matrix of the ith link of the moving platform. The compliance matrices of the intermediate legs and the ith link of the moving platform are calculated by means of the stiffness model of a cantilever beam, namely,

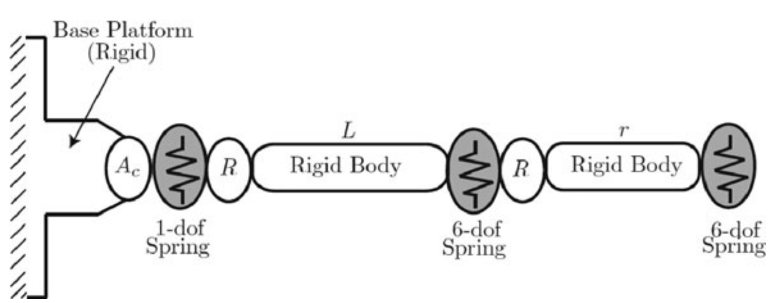

Fig. 3 Flexible model of a single kinematic chain of the 3-PRR PPM, A_c stands for an actuating joint and R for a revolute joint

$$\mathrm{K}_L^{i-1} = \begin{bmatrix} \frac{L}{EA} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{L^2}{3LI_z} & 0 & 0 & 0 & \frac{L^2}{2EI_z} \\ 0 & 0 & \frac{L^3}{3EI_y} & 0 & -\frac{L^2}{2EI_y} & 0 \\ 0 & 0 & 0 & \frac{L}{GI_x} & 0 & 0 \\ 0 & 0 & -\frac{L^2}{2EI_y} & 0 & \frac{L}{EI_y} & 0 \\ 0 & \frac{L^2}{2EI_z} & 0 & 0 & 0 & \frac{L}{EI_z} \end{bmatrix} \quad (18)$$

L is the length of the beam, i.e., $L = L_\mathrm{b}$ for the intermediate legs and $L = r$ for the moving platform links. A is the cross-sectional area of the beam, i.e., $A_{L_\mathrm{b}} = \pi r_j^2$ and $A_r = \pi r_p^2$. $I_z = I_y$ is the polar moment of inertia about y and z axes, i.e., for the intermediate legs and the moving platform links, their expressions are $\pi r_j^4/4$ and $\pi r_p^4/4$, respectively. $I_x = I_y + I_z$ is the polar moment of inertia about the longitudinal axis of the beam. E is the Young modulus of the material and G is its shear modulus.

$\mathbf{J}_\theta^i$ of size 6×13 is the Jacobian matrix related to the virtual springs and $\mathbf{J}_q^i$ of size 6×2, the one related to the passive joints. $\mathbf{f}_i$ is the wrench applied on the ith leg of the 3-PRR PPM at the centroid of the moving platform and $\delta\mathbf{t}_i$ is the corresponding translational and rotational displacements vector. Therefore, the Cartesian stiffness matrix $\mathbf{K}_i$ of the ith leg defining the motion-to-force mapping is obtained from Eq. (16).

$$\mathrm{f}_i = \mathrm{K}_i \delta \mathrm{t}_i \quad (19)$$

Finally, the Cartesian stiffness matrix $\mathbf{K}$ of the 3-PRR PPM is found with a simple addition of $\mathbf{K}_i$ matrices, namely,

$$\mathrm{K} = \sum_{i=1}^{3} \mathrm{K}_i \quad (20)$$

3 Multiobjective Design Optimization

In general, the design process of PKMs simultaneously deals with two groups of criteria, one relates to the kinematic properties while the other relates to the kinetostatic/dynamic properties of the mechanism. Both of these groups include a number of performance measures that essentially vary throughout the workspace but remain within the prescribed bounds. Kinematic aspects are comparatively less complex and are usually based on the concept of critical points whereas kinetostatic aspects work with a detailed description of the structure and their evaluation is usually time consuming. Indeed, one of the major design issues in kinetostatic design is the computation of the stiffness matrix [22]. Accordingly, a multiobjective design optimization approach is proposed based on performance measures/criteria from both kinematic and kinetostatic domains. On the one hand, this approach deals with the geometric/kinematic design in order to determine the PKM geometry including the link lengths and the joint limits. On the other hand, it considers the kinetostatic design to determine the size and the mass properties of the links.

3.1 Optimization Objectives

The multiobjective optimization problem aims to determine the optimum geometric parameters of a PKM in order to maximize its workspace as well as to minimize the mass of the mechanism in motion. Here, the workspace of the mechanism is discretized and the considered performance measures and constraints are evaluated and verified for each point.

3.1.1 Mass in Motion of the Mechanism

The mass in motion of the mechanism is considered to be the first objective function of the optimization problem. Mass and inertia are functions of manipulator dimensions, i.e., link lengths, cross-sectional area, thickness. Hence, in general, the mass in motion m_t of the mechanism is composed of the mass of the platform, m_pf, the mass of the three intermediate bars, m_b, and the mass in motion of the three prismatic actuators, m_s:

$$m_\mathrm{t} = m_\mathrm{pf} + 3m_\mathrm{b} + 3m_\mathrm{s} \quad (21)$$

Since the actuators are fixed, their mass is considered to be constant while the mass of the other two components can be easily calculated by using the geometry of the components and the density d of their material, given as,

$$m_\mathrm{pf} = \pi r_\mathrm{p}^2 r d, \qquad m_\mathrm{b} = \pi r_\mathrm{j}^2 L_\mathrm{b} d \quad (22)$$

Consequently, the first objective function of the optimization problem is written as:

$$f_1(\mathrm{x}) = m_\mathrm{t} \rightarrow \min \quad (23)$$

$\mathbf{x}$ being the design variable vector of the mechanism.

3.1.2 Regular Workspace Size

The workspace is one of the most important design issues as it defines the working volume of the robot/manipulator and determines the area that can be reached by a reference frame located on the moving platform or end-effector [12, 23]. The size and shape of the workspace are of primary importance for the global geometric performance evaluations of the manipulators [24].

The quality of the workspace that reflects the shape, size, presence of singularities is of prime importance in PKM design. Workspace based design optimization of parallel mechanisms can usually be solved with two different formulations. The first formulation aims to design a manipulator whose workspace contains a prescribed workspace and the second approach aims to design a manipulator, of which the workspace is as large as possible. However, maximizing the workspace may result in poor design with regard to the manipulator dexterity and manipulability [12]. This problem can be solved by properly defining the constraints of the optimization problem. Here, the multiobjective optimization problem of PKMs is based on the formulation of workspace maximization, i.e., the determination of the optimum geometry of PKM in order to maximize a regular-shaped workspace. The workspace size can be defined by its geometric shape parameters like the radius of a cylindrical/spherical workspace or the sides of the cube for a cubic workspace.

In the scope of the paper, a cylindrical workspace defined with its radius R_w is considered. Furthermore, at each point of the workspace, an angular rotation range $\Delta\phi = 20°$ of the platform about the Z-axis can be achieved. A 3-dimensional schematic of the regular shaped workspace is shown in Fig. 4, where x_c and y_c are the Cartesian coordinates of the regular dextrous workspace center and ϕ_c is the orientation of the platform at its home-posture (see Fig. 1).

Consequently, in order to maximize the manipulator workspace, the second objective of the optimization problem can be written as:

$$f_2(\mathrm{x}) = R_w \rightarrow \max \tag{24}$$

3.2 Optimization Constraints

Besides, the geometric and actuator constraints of the PKM, conditioning of the kinematic Jacobian matrix and accuracy

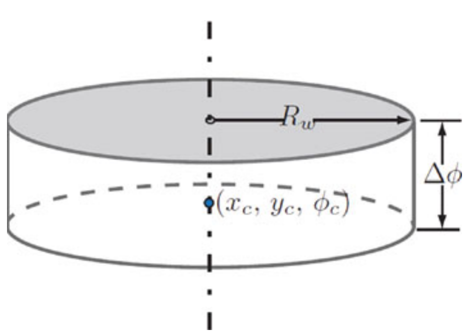

Fig. 4 3-PRR regular workspace

obtained from the stiffness characteristics of the mechanism are considered. Constraining the conditioning of the Jacobian matrix guarantees singularity free workspace whereas limits on accuracy consideration ensure sufficient mechanism stiffness.

3.2.1 Geometric Constraints

The first constraint is related to the mechanism assembly, namely,

$$L_b + r \geq R/2 \tag{25}$$

In order to avoid intersections between prismatic joints, the lower and upper bounds of the prismatic lengths are defined as follows:

$$0 < \rho i < \sqrt{3}R \tag{26}$$

3.2.2 Condition Number of the Kinematic Jacobian Matrix

The condition number $\kappa_F(\mathbf{M})$ of a $m \times n$ matrix $\mathbf{M}$, with $m \leq n$, based on the Frobenius norm is defined as follows,

$$\kappa_F(\mathrm{M}) = \frac{1}{m}\sqrt{\mathrm{tr}(\mathrm{M}^T\mathrm{M})\mathrm{tr}[(\mathrm{M}^T\mathrm{M})^{-1}]} \tag{27}$$

Here, the condition number is computed based on the Frobenius norm as the latter produces a condition number that is analytic in terms of the posture parameters whereas the 2-norm does not. Besides, it is much costlier to compute singular values than to compute matrix inverses.

The terms of the direct Jacobian matrix of the 3-PRR PPM are not homogeneous as they do not have same units. Accordingly, its condition number is meaningless. Indeed, its singular values cannot be arranged in order as they are of different nature. However, from [25] and [26], the Jacobian can be normalized by means of a normalizing length. Later on, the concept of characteristic length was introduced in [27] in order to avoid the random choice of the normalizing length. For instance, the previous concept was used in [18] to analyze the kinetostatic performance of manipulators with multiple inverse kinematic solutions, and therefore to select their best working mode.

Accordingly, for the design optimization of 3-PRR PPM, the minimum of the inverse condition number of the kinematic Jacobian matrix, $\kappa^{-1}(\mathbf{J})$, is supposed to be higher than a prescribed value, say 0.1, throughout the manipulator workspace, for any rotation of its end-effector, i.e.,

$$\min(\kappa^{-1}(\mathrm{J})) \geq 0.1 \tag{28}$$

3.2.3 Accuracy Constraints

The position and orientation accuracy is assessed by using the stiffness parameters of the mechanism. Let (δx, δy, δz) and ($\delta\phi_x$, $\delta\phi_y$, $\delta\phi_z$) be the position and orientation errors of the end-effector subjected to external forces (F_x, F_y, F_z) and torques (τ_x,τ_y,τ_z). The constraints related to the accuracy of the manipulator are defined as follows:

$$\begin{array}{lll} \delta x \leq \delta x^{\max} & \delta y \leq \delta y^{\max} & \delta z \leq \delta z^{\max} \\ \delta\phi_x \leq \delta\phi_x^{\max} & \delta\phi_y \leq \delta\phi_y^{\max} & \delta\phi_z \leq \delta\phi_z^{\max} \end{array} \tag{29}$$

($\delta x^{\max}$, $\delta y^{\max}$, $\delta z^{\max}$) being the maximum allowable position errors and ($\delta\phi_x^{\max}, \delta\phi_y^{\max}, \delta\phi_z^{\max}$) the maximum allowable orientation errors of the end-effector. These accuracy constraints can be expressed in terms of the components of the mechanism stiffness matrix and the wrench applied to the end-effector. Let us assume that the accuracy requirements are:

$$\sqrt{\delta x^2 + \delta y^2} \leq 0.0001\,\text{m} \tag{30a}$$

$$\delta z \leq 0.001\,\text{m} \tag{30b}$$

$$\delta\phi z \leq 1\,\text{deg} \tag{30c}$$

If the end-effector is subjected to a wrench, whose components are $\| F_{x,y} \| = F_z = 100\text{N}$ and $\Box\tau_z = 100\,\text{Nm}$, then the accuracy constraints can be expressed as:

$$k_{xy}^{\min} \geq \left\|F_{x,y}\right\| / \sqrt{\delta x^2 + \delta y^2} = 10^6\text{N.m}^{-1} \tag{31a}$$

$$k_z^{\min} \geq F_z/\delta z = 10^5\text{N.m}^{-1} \tag{31b}$$

$$k_{\phi z}^{\min} \geq \tau_z/\delta\phi z = \frac{10}{\pi/180}\text{N.m.rad}^{-1} \tag{31c}$$

3.3 Design Variables

Along with the above mentioned geometric parameters (R, r, L_b) of the 3-PRR PPM, the dimension of the circular-cross-section of the intermediate bars defined with radius r_j and the circular-cross-section of the platform bars defined with r_p are considered as design variables, also called decision variables. The platform is assumed to be made up of three circular bars, each of length r. Hence, the design variable vector **x** is given by:

$$\text{x} = [\ R\ r\ L_\text{b}\ r_\text{j}\ r_\text{p}\ ]^\text{T} \tag{32}$$

3.4 Multiobjective Optimization Problem Statement

The Multiobjective Optimization Problem (MOO) for a 3–PRR PPM can be stated as:

Find the optimum design parameters x of a 3–PRR PPM in order to minimize the mass in motion of the mechanism and to maximize its regular shaped workspace subject to some design constraints, i.e., the inverse condition number of the kinematic Jacobian matrix and accuracy are to be higher than prescribed values throughout the manipulator workspace.

Mathematically, the problem can be written as:

$$\begin{array}{ll} \text{minimize} & f_i(\text{x}) = m_\text{t} \\ \text{maximize} & f_2(\text{x}) = R_\text{w} \\ \text{over} & \text{x} = [\ R\ r\ L_\text{b}\ r_\text{j}\ r_\text{p}\ ]^\text{T} \\ \text{subject to :} & g_1 : L_\text{b} + r \geq \frac{R}{2} \\ & g_2 : 0 < \rho_i < \sqrt{3}R \\ & g_3 : \kappa^{-1}(\mathbf{J}) \geq 0.1 \\ & g_4 : k_{xy}^{\min} \geq \dfrac{F_{x,y}}{\sqrt{\delta x^2 + \delta y^2}} = 10^6 \\ & g_5 : k_z^{\min} \geq \dfrac{F_z}{\delta_z} = 10^5 \\ & g_6 : k_{\phi_z}^{\min} \geq \dfrac{\tau_z}{\delta\phi_z} = \frac{10}{\pi/180} \\ & \text{x}_\text{lb} \leq \text{x} \leq \text{x}_\text{ub} \end{array} \tag{33}$$

where $\mathbf{x}_\text{lb}$ and $\mathbf{x}_\text{ub}$ are the lower and upper bounds of $\mathbf{x}$, respectively.

4 Results and Discussions

The multiobjective optimization problem (33) is solved by means of modeFRONTIER [28] and by using its built-in multiobjective optimization algorithms. MATLAB code is incorporated in order to analyze the system and to get the numerical values for the objective functions and constraints that are analyzed in modeFRONTIER for their optimality and feasibility. The lower and upper bounds of the design variables are given in Table 1. The manipulator is supposed to be built in steel of density $d = 7850$ kg/m^3 and Young modulus $E = 210 \times 10^9$ N/m^2.

Table 1 Lower and upper bounds of the design variables

Design variable	R	r	L_b	r_j	r_p
Lower bound (lb) [m]	0.5	0.5	0.5	0	0
Upper bound (ub) [m]	4	4	4	0.1	01

Table 2 modeFRONTIER algorithm parameters

Scheduler	MOGA-II
Number of iterations	200
Directional cross-over probability	0.5
Selection probability	0.05
Selection probability	0.1
DNA (DeoxyriboNucleic Acid) string mutation ratio	0.05
DEO algorithm	Sobol
DOE number of designs	30
Total number of iterations	$30 \times 200 = 6000$

Table 3 Three Pareto optimal solutions

Design ID	Design variables					Objectives	
	R [m]	r [m]	L_b [m]	r_j [m]	r_p [m]	m_t [kg]	R_w [m]
I	1.412	0.319	0.620	0.026	0.023	44.5	0.110
II	3.066	1.283	1.896	0.036	0.056	484.8	1.207
III	3.872	1.947	1.977	0.039	0.096	1545.6	1.609

For each design iteration, workspace limits are calculated based on the set of design parameters of the mechanism. Then, workspace discretization is performed with respect to its x and y coordinates and with respect to the orientation angle ϕ of the moving platform. The constraints of the problem are evaluated at each grid point of the workspace.

A multiobjective genetic algorithm (MOGA) is used to obtain the Pareto frontier based on the mechanism mass and the workspace radius. modeFRONTIER scheduler and Design Of Experiments (DOE) parameters are given in Table 2. MATLAB is used to process and analyze the system for any individual of the current population (generated by the modeFRONTIER scheduler). Corresponding to each population set, MATLAB returns the output variables that are analyzed by modeFRONTIER for the feasible solutions according to the given constraints. At the end, the Pareto-optimal solutions are obtained from the generated feasible solutions.

The Pareto frontier is shown in Fig. 5 whereas the design variables and the corresponding objective functions for two extreme and one intermediate Pareto optimal solutions, as shown in Fig. 5, are depicted in Table 3.

The designs associated with the three foregoing solutionsare shown in Fig. 6.

Figure 7 illustrates the variational trends as well as the inter-dependency between the objective functions and design variables by means of a scatter matrix. The lower triangular part of the matrix represents the correlation coefficients, ξ, whereas the upper one shows the corresponding scatter plots. The diagonal elements represent the probability density charts of each variable. The correlation coefficients

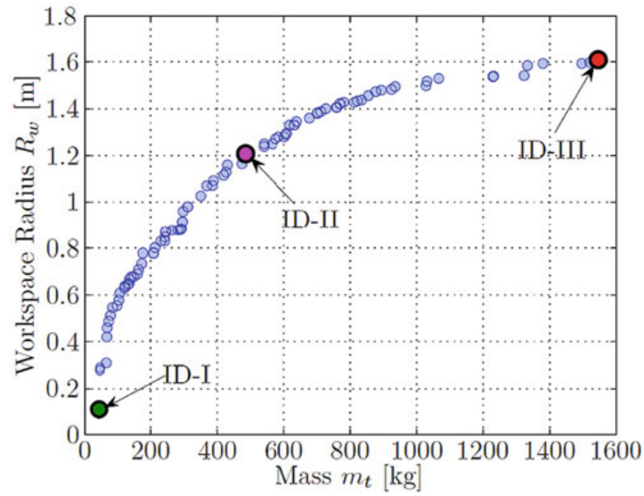

Fig. 5 Pareto frontier for 3-PRR optimization problem

vary from –1 to 1. Two variables are strongly dependent when their correlation coefficient is close to 1 or –1 and independent when the latter is null. Figure 7 shows that:

- Both objectives functions m_t and R_w are strongly dependent as their correlation coefficient is equal to 0.907;
- Both objectives functions m_t and R_w are strongly dependent on all design variables as all of the corresponding correlation coefficients are greater than 0.7;
- R_w ($\xi \geq 0.830$) is slightly more dependent than m_t ($0.711 \leq \xi \leq 0.981$) of the design variables.

Figure 8 illustrates the design variables R, r, L_b, r_j and r_p as a function of R_w for the Pareto-optimal solutions. It is noteworthy that the higher R_w, the higher the design variables. It is apparent that the variations in variables R, r, L_b and r_j with respect to (w.r.t.) R_w are almost linear whereas the variations in r_p w.r.t. R_w is not. As a matter of fact, it should be due to the fact that the higher the size of the mechanism the higher the bending of the moving platform links whereas the intermediate links are mainly subjected to tension and compression. Finally, the three sets of design variables corresponding to the Pareto-optimal solutions depicted in Fig. 5 are shown in Fig. 8 by means of the green, pink and red symbols.

5 Conclusions

In this chapter, the problem of dimensional synthesis of parallel kinematics machines was addressed. A multiobjective design optimization problem was formulated in order to determine optimum structural and geometric parameters of

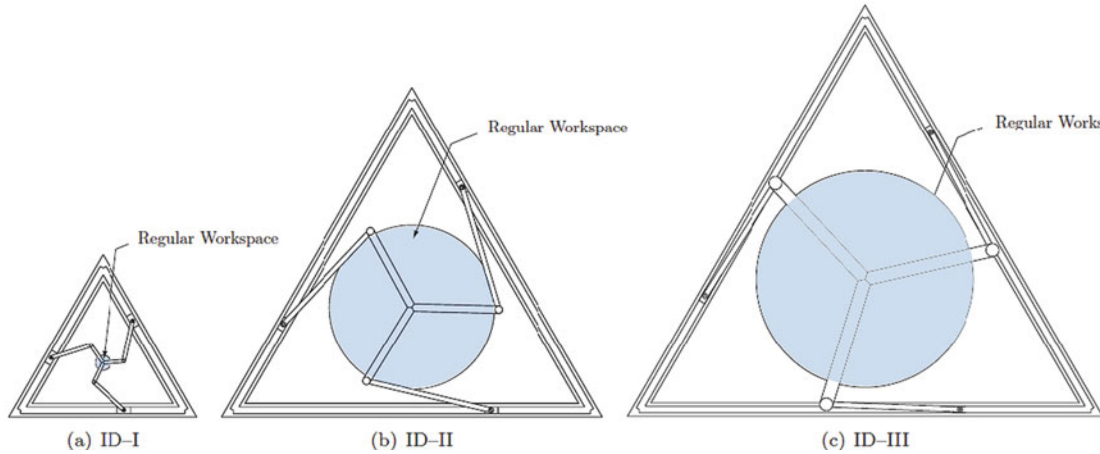

Fig. 6 CAD Designs of three Pareto-optimal solutions

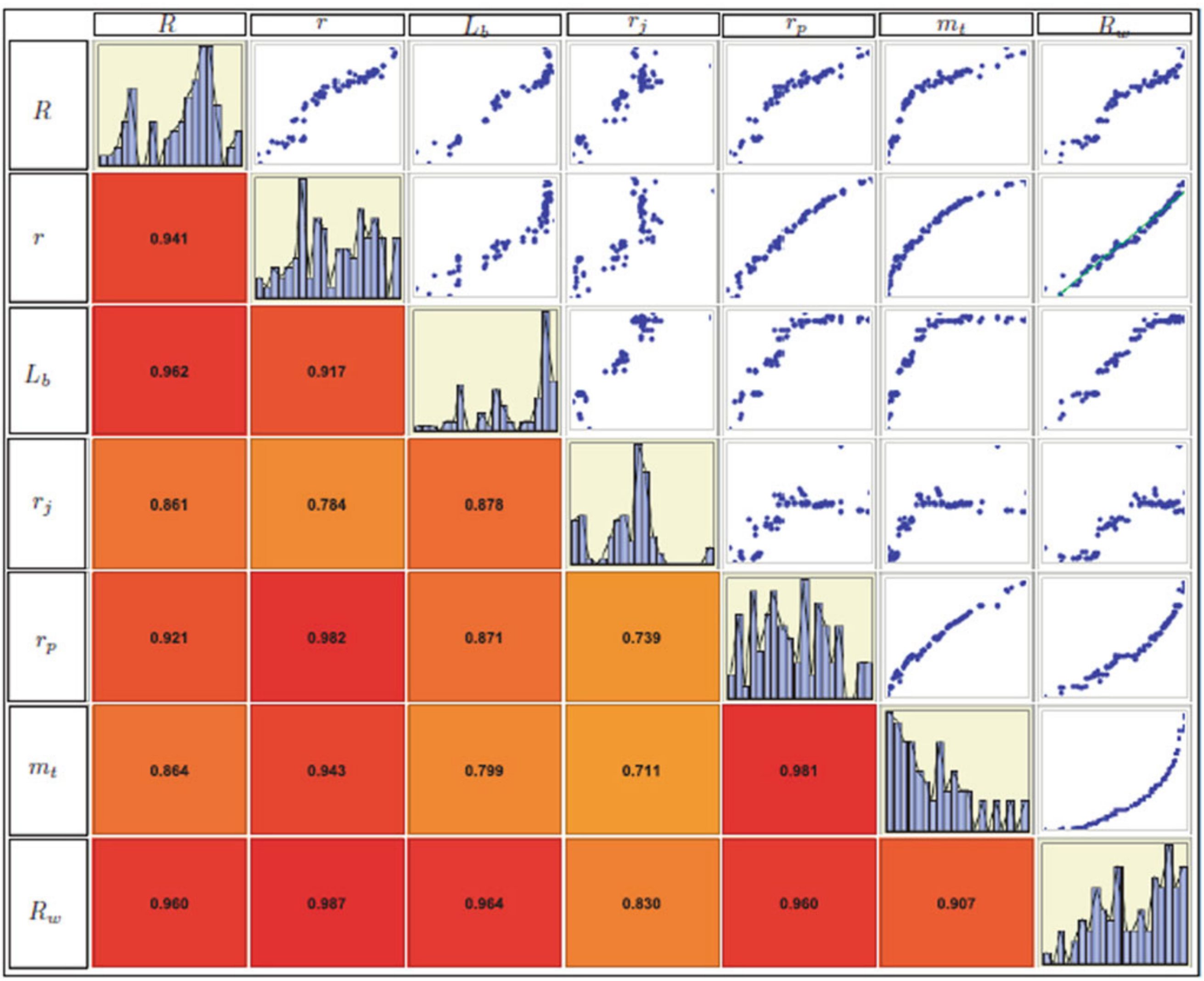

Fig. 7 Pareto Scatter matrix illustrating the correlations between the objective functions and the design variables

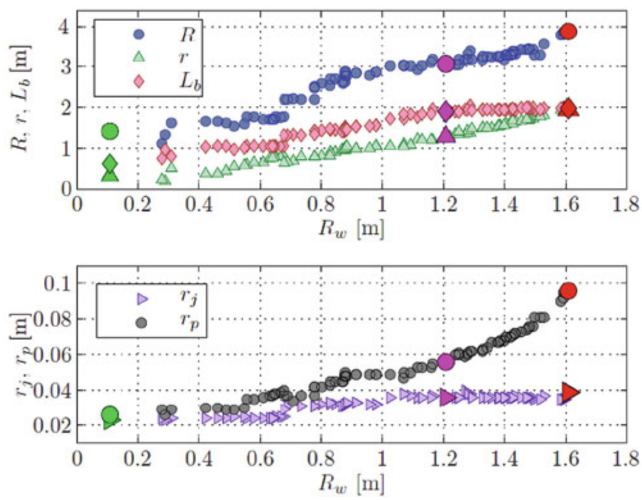

Fig. 8 Design variables as a function of R_w for the Pareto-optimal solutions

any parallel kinematics machine. The proposed approach is similar to that used in [29] but we took into account the mass and the regular workspace instead of considering the entire volume of the manipulator. The proposed approach was applied to the optimum design of a three-degree-of-freedom planar parallel manipulator with the aim to minimize the mass in motion of the mechanism and to maximize its regular shaped workspace.

It is apparent that other performance indices can be used as constraints. However, they cannot necessarily be used as objective functions as the latter are usually formulated as a sum of an index over all the manipulator workspace. As another constraint, we could use the collisions between the legs of the manipulator as illustrated in [4].

Our future works will deal with the multiobjective design optimization and the comparison of 3-DOF planar parallel manipulators of different architectures as well as the optimization of the cross-section type of their links.

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Value, Risk and Cost Management in Global Product Development

Product-Driven Process Value Analysis

Y. Borgianni, G. Cascini, and F. Rotini

Abstract The paper describes a methodology to support business process re-engineering by mapping product requirements to product development phases in order to analyze their contribution to value creation. The methodology has been already validated by the authors in different industrial sectors through real case studies [1], that were all characterized by well established business processes, needing improvements to preserve their competitiveness in the marketplace. In this chapter the effectiveness of the methodology in identifying process criticalities is tested with regards to industrial processes experiencing under capacities in satisfying the market demand as well as concerning not yet established business ideas. The task is performed by considering the wood pellet production process as a case study.

Keywords Process value analysis · Customer satisfaction · Business process re-engineering · Product requirements

List of Abbreviations

BPR	Business Process Re-engineering
BSC	Balanced Scorecard
CR	Customer Requirement
EMS	Energy, Material, Signal
ETO	Engineering To Order
IDEF	Integration DEFinition
LHV	Lower Heating Value
POS	Phase Overall Satisfaction
POV	Phase Overall Value
PSSs	Product and Service Systems
RES	RESources
TQM	Total Quality Management
TRIZ	Theory of Inventive Problem Solving
VA	Value Analysis

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1 Introduction

All the products have to pursue continuous improvements in order to satisfy new customer requirements or novel market demands concerning their whole lifecycle. This task implies an evolution of the production process at different levels. In some circumstances minor reorganizations in the design or production phases can be sufficient to fulfill the evolving product requirements; besides, these actions usually bring only to limited improvements mainly focused on preserving the competitiveness of the product in the marketplace.

In other market circumstances the companies have to develop more remarkable innovations. Boundary conditions, such relevant discontinuities in customer perceived value and preferences, lead to the implementation of radical technological changes [2]. Besides, limitations of available resources are a common trigger for impending transitions of mature technical systems [3] or even established service industries [4]. Disruptive innovations can be brought also by performing a careful analysis of the possible aspects of value that consumers might care about, such as way of using, further technical or emotional features, resources consumption, maintenance, environmental impact, customer care, end of product lifecycle. Such approach, that is viable to create new market opportunities, implements a product planning strategy aimed at making the competition irrelevant, that determines a new value curve strongly different than the previous one [5].

However, novel product ideas often show relevant problems to access market due to a large amount of factors such as design or manufacturing costs [6], organizational issues [7], required technologies or materials [8], relevant drawbacks [9], resources consumption [10]. All these kinds of limitations represent significant hurdles to exploit new business

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opportunities, notwithstanding the realized products or the delivered services are viable to occupy promising market space.

Consequently the implementation of new product ideas requires a radical transformation of the production process encompassing the reorganization of its phases and the reallocation of the resources, that have to be oriented towards the fulfillment of the identified customer requirements. Thus the task includes recognizing new productivity requirements, product performances to be enhanced, new functions to be fulfilled, new properties or features of the system. In order to prioritize the actions to be taken, the guidelines for performing the changes of the production process have to be driven through the identification of value bottlenecks. With the aim of performing this task and defining re-engineering activities aimed at obtaining improvements of a business process that are focused on the impact that each phase has on the value generated for the users, a methodology based on Process Value Analysis has been developed by the authors [1]. The proposed approach allows the identification of proper metrics to assess a set of product/service requirements intended to ensure customer satisfaction. On the base of such metrics the evaluation of the impact of each phase in the perceived value of products and/or services is performed with respect to the employed resources. The results of this assessment are used to systematically synthesize suitable guidelines for both process evolution strategies and resource reallocation activities, allowing to preserve or improve market competitiveness of products and/or services.

Several case studies in very different industrial sectors have been analyzed with the aim to test the robustness of the proposed method. These case studies were mainly related to well established business processes, needing improvements to preserve the competitiveness of the delivered products/services in a crowded marketplace.

In this chapter the application of the methodology in an emerging field is presented, i.e. the woody pellet production process. This sector presents high business opportunities in Italy since the market demand of such kind of energy sources has grown dramatically in the last 5 years. However the poor performance arising out of the industrial processes still under development, doesn't allow the complete exploitation of the biomass resources, thus the market demand of woody fuels remains unsatisfied. In such context the paper tests the applicability of the developed approach also for industrial processes experiencing such kind of under capacities, as well as concerning not yet established business ideas.

The paper presents: in Sect. 2, a brief literature review of tools and methods dedicated to support business process re-engineering tasks; in Sect. 3, the approach developed by the authors in a version customized according to the objectives faced in the case study; a detailed description of its application to the production process of solid woody fuel in Italy in Sect. 4. The results arising from the case study case are discussed in Sect. 5, that includes also the conclusions.

2 Literature Review

Many methods, that are mainly related to the field of the Business Process Re-engineering (BPR) [11–13], have been developed aimed at addressing redesigning and innovation tasks of business and manufacturing systems.

An integrated multidimensional process improvement methodology has been proposed in [14] to address the yield management, process control and cost management problems for a production process. The Total Quality Management (TQM) is used to manage the cost of the system according to the quality requirements and a discrete event simulation is used to perform process re-engineering and process improvement.

In [15] a method has been proposed which supports the practitioners in developing a new improved business process starting from the current design based on a heuristic approach. The method has been extrapolated from different successful best practice approaches to the BPR problems available in the literature survey. They have been synthesized in a check list to support process redesigning by taking into account different management approaches: Total Cycle Time compression, Lean Enterprise and Constraints Management.

In [16] an investigation of BPR methodologies employed in different companies making products on engineering to order basis (ETO) that typically find business opportunities by the ability to respond to customer requirements, has been performed. The results show that BPR methodologies cannot be applied to such kind of companies since they are not able to manage different business units as in the case of collaborating companies.

A methodology to assist the user in identifying the most appropriate lean manufacturing tools and techniques to address the problems of a particular company through a quantitative compatibility assessment has been proposed in [17]. The results confirm that lean manufacturing tools may have a major impact only on specific areas of the business but not for companies experienced problems in areas such as under capacity, scheduling and innovation in products and processes, which are all topics, that are not directly influenced by lean manufacturing methods.

The approach based on Balanced Scorecard (BSC) [18] provides a systematic tool for BPR by combining financial and nonfinancial performance indicators in a coherent measurement system. Four metrics are defined according to a selected strategy, and the company's processes are aligned towards this strategy. The company is evaluated in four areas: the financial perspective; the customer satisfaction;

the internal business process view based on the concept of the value chain; a final index comprising the innovation and learning perspective. As stated in [19] BSC suffers from limits based on invalid assumptions about the innovation economy: its rigidity, its conception of knowledge and innovation as a routine process and its focus on the internal processes of the company, neglecting the relationships with the environment, make the BSC an insufficient tool for understanding and dealing with the innovation economy.

A number of works approach the problem of dealing with concurrent issues in terms of costs management and product requirements; a recent example is [20], where the integration of Value Engineering and Target-costing techniques is proposed to support the product development process in an automotive company. Such a methodology was applied to a case study aimed at improving costs and performances of a vehicle engine-starter system, according to customer and company needs.

Several works in literature demonstrate that BPR has failed to meet its expectations; among the others [21], shows that 60–80% of BPR initiatives have been unsuccessful. The most frequent and harsh critique concerns the strict focus on efficiency and technology and the disregard of people in the organization that is subjected to a reengineering initiative. Very often the label BPR was used for major workforce reductions with the aim to decrease organizational and production costs, instead of being able to suggest any kind of improvement based on process innovation. Moreover the analysis performed in [22] suggested that in order to obtain successful BPR initiatives, redesign efforts should be focused not only on cost and time reduction but mainly on the areas of the business process having the most direct impact on customer value. These results show that managers must reengineer their core processes starting from the customer perspective.

In such a context the Product and Service Systems (PSSs) approach has been developed in [23] with the aim to provide a product additional value, base a growth strategy on innovation in a mature industry and improve the total value for the customer thanks to increased servicing. However there are few examples of complete PSSs designed on a life cycle basis in companies. This is due to a number of uncertainties concerning the characteristics of the PSSs, among the others:

- readiness to adopt the PSSs into a company's strategic decisions. The shift from selling products to providing PSS entails substantial changes in the companies' structure and organizational frameworks, production and marketing strategies;
- readiness to accept the PSSs by consumers; little research has been conducted on evaluating the impact of PSSs paradigms and their profitability for consumers.

In order to overcome these limits a general methodological framework for PSSs design and implementation still requires to be developed.

Many other approaches available in literature suggest guidelines for business re-engineering activities mainly focused on cost reduction without taking into account any aspect of the benefits the product or service generates for customers.

3 Methodological Proposal

The identification of value bottlenecks is performed by a classification of the business process phases based on the value they generate for the customer in terms of product requirements, taking into account the amount of the employed resources. The procedure for the identification of the phases that do (or do not) contribute at a proper extent to generate value along the business process can be summarized in the following steps:

1. information gathering, carried with proper techniques, allowing to determine the relevant process phases and the extent of the employed resources;
2. identifying relevant customer requirements and their relative importance in order to create value;
3. determining the degree at which the phases contribute to fulfil the previous mentioned requirements;
4. calculating the overall value of each phase;
5. evaluating the directions of improvement for the considered business process.

In the following a brief description of the above mentioned steps already proposed in [1] is reported, with a specific emphasis on the customization needed according to the objectives of this chapter.

3.1 Gathering Information and Building the Model of the Current Business Process

The first step of the methodology consists in performing an accurate collection of the information about the process and its operations, such as EMS (energy, material, signal) flows, technologies involved, products and services delivered, knowledge management means and criteria and other resources. The information gathering allows to segment the business process in a set of phases.

If well-established business and manufacturing practices are usually documented in books and in the scientific literature, poor knowledge can be gathered within new, pioneering or under development industrial processes. Thus experimental data and the tacit knowledge belonging to enterprises' internal resources (managers, directors, but even employees) play a major role in collecting information for a starting business. Within business and manufacturing processes it is recommended to employ proper modelling techniques, such as the ones of IDEF family, that play an unquestionable role in making the acquisition of knowledge related to the as-is state easier. Among these modelling tools, IDEF0 allows to create diagrams suitable to represent the functions performed within business and manufacturing processes. However the technique fits processes representation [24], since the system functions that can be modelled include activities, actions, operations.

IDEF0's graphical format with "box and arrows" allows within process modelling to schematize the operations involved (the boxes), as well as EMS flows and transformations, controls, employed technologies and personnel competencies (through the formalized arrows). Thanks also to its hierarchal representation of activities, that is useful in revealing further details of the business model, IDEF0 returns as an output the whole set of phases, univocally defined by their function and flows.

Although IDEF0 allows to highlight, along the whole business process, a large amount of inputs and outputs, in the context of this research, the analysis requires a more careful investigation about the resources employed in the system. The information about monetary flows, amount of labour, operational times, needs for physical space and the whole set of involved resources and harmful effects generated when performing the process (i.e. environment pollution, tools and machinery consumption) has to be summarized in the process model. Particular attention has to be paid towards those resources and drawbacks that constitute significant hurdles to access the market in consideration of the as-is process. The IDEF0 model has been here customized in order to map these flows of resources. It is worth to mention that in scientific literature there are several papers where the original formalism of the IDEF language has been customized according to the specific tasks or objectives to be faced, as in [25].

3.2 Identifying the Benefits and the Performance of the Process

This step is addressed to evaluate the benefits generated by the business process in terms of their own contribution to determine customer perceived value and satisfaction. The task is accomplished through the evaluation of the value adding attributes pertaining the manufactured products or the delivered services.

In the investigation of potential new business the attention is firstly focused on satisfying the customer requirements at an extent comparable with further competitors, besides specific objectives of the developed project and the minimal technical attributes, requested by laws or other restrictions [26]. Since all these requirements represent attributes that the product should hold in order to access the market, it is assumed that the benefits originated from the business process reside in fulfilling these requirements.

According to this statement each requirement is indicated with the denotation CR and it is weighted by a relative relevance index (R) in accordance to its role in determining the contribute to let market access and to boost customer perceived value. A scale from 1 to 5 will be adopted for this purpose, whereas 5 represents the highest importance.

3.3 Identifying the Phases' Extent in Generating Benefits

In order to relate the business process steps with the value perceived by the customers, it is hereby remarked that each phase contributes totally or partially to ensure the product requirements. Thus, in the scope of business process reengineering activities, the proposed procedure requires mapping the product attributes underlying the accomplishment of each CR. Subsequently the phases, properly identified in the step 1, that modify or somehow deal with those attributes are evaluated by the business process experts in order to define their relative contributions in fulfilling each CR. These relative contributions give the possibility to determine for each phase its own Phase Overall Satisfaction (POS), representing its extent to bring customer contentment and to gain market acceptance. The phase coefficients POS_j are calculated as follows:

$$\text{POS}j = \sum_i k_{ij} \times R_i \tag{1}$$

where:

- k_{ij} is the relative contributions addressed to the jth phase in ensuring the achievement of the ith CR;
- Ri represents the relative relevance index of the ith attribute.

3.4 Determining the Overall Value of the Process Phases

The purpose of this step is to perform a comparison among the process phases in terms of parameters related to customer satisfaction and the resources needed for their accomplishment. This task is accomplished by evaluating the ratio between the POS of each phase and the related resources that are employed; such approach is based on the logic of Value Analysis (VA) [27]. With respect to the traditional application of VA mainly addressed to evaluate the ratio between performance of a function and costs, in such context it is applied considering the total amount of resources spent by the business process phases to guarantee the CRs, as well as drawbacks and harmful effects arising in pursuance of the activities. Such modified ratio represents the degree of ideality of each phase as defined in the TRIZ Theory [28], thus representing an evolution of the well-ascertained value expression of VA, that relates just benefits and costs. Moreover, in its widest meaning, the degree of ideality indicates a ratio between the value delivered by a certain system and all types of expenses and investments needed to produce this value [29].

Within the context of business processes it is suitable to consider the whole range of resources spent (occupied space, information and know-how, labour time, energy, materials, dead times) and measure their extent, in order to use value and ideality formulations for calculating quantitative indicators. Long elapsed times to perform the phases can represent hurdles to gain competitiveness in the market. The activities duration has to be considered, although quick response strategies [30] are mainly focused to established business sectors, that include time among the most meaningful competitive factors, due to the need to speed up the continuous introduction of new items in the market. All the kinds of the other employed resources can be compared in terms of the expenses deriving from their employment, so to be evaluated with uniform units of measurement.

With regards to the harmful effects, they will be soundly considered in value calculation when representing barriers to access the market or problems affecting the stability of the system, as well as the repeatability of the process.

When resources costs, meaningful elapsed times and harmful effects coexist in the business process, experts have to weigh their relative relevance, introducing corrective coefficients for the calculation of phases overall value.

Due to the previous evaluations, the overall value of the jth process phases (POV_j) is calculated through the formula (Eq. (2)):

$$\mathrm{POV}j = \frac{\mathrm{POS}j}{c \times C_j + t \times T_j + h \times \mathrm{HF}_j} \tag{2}$$

where:

- C_j represents the total costs incurred to carry the jth phase;
- T_j indicates the time spent in completing the jth phase;
- HF_j is the estimated extent of harmful effects arising from the jth phase;
- c, t and h stand for the coefficients that measure the relevance of expenditures, elapsed times and drawbacks in hindering the market access.

The value of the latter coefficients depends on the maturity of the technology under analysis, as analyzed in [31].

3.5 Prioritizing the Directions for Improvement

This stage of the methodology is meant to rank the process phases according to the calculated values. The POV indicators are suitable to identify business process strong points and constraints among the phases. The phases showing a high POV rate can be considered to be tailored to the business process and their employed resources are well spent in generating customer satisfaction, whereas the ones with low scores can represent problematic issues and bottlenecks in the value creation process. By the point of view of value creation the most problematic phases have to be analyzed carefully, since they have the biggest priority in performing modifications for Business Process Reengineering. Through such analysis suitable actions can be defined to perform process re-engineering tasks focused to preserve/improve the value perceived by the customers.

4 Case Study: Wood Pellet Production

Solid biofuel obtained by the sustainable exploitation of forest resources represents a relevant complementary source of energy to oil and its derivatives. In the last 2 years the market demand of solid biofuel in Italy has dramatically grown and it represents a business opportunity for a lot of rural areas: one of these is the Appennino Tosco-Emiliano. Two different kinds of solid biofuel are obtained by the exploitation of the forest resources and sawdust:

- wood chips: pieces of wood having overall dimensions of $25 \times 30 \times 20$ mm, maximum moisture content of 20% in weight, average market price 70 €/Ton;
- pellets: cylinders of pressed sawdust having a diameter of 6 or 8 mm, height of 35 mm, moisture content of 10% in weight, average market price 180 €/Ton.

Table 1 shows an example of local exploitation of biomass resources, referring to a small area located in the Appennino Tosco-Emiliano (Italy). In this region the amount of biomass obtained by the sustainable exploitation of forests during a year, may constitute an energy source able to satisfy the

Table 1 Woody biomass resources available in the Appenino Tosco-Emiliano (tons/year)

Origin	Moisture content (in weight) (%)	Estimated availability	Estimated availability after 10 years
Wood from industry processes	10	5000	6000
Wood coming from forest management	35–50	25000	50,000
Wood coming from urban green management	45–50	2000	10,000

needs of about 6600 housing units making them almost independent from the oil derivatives. The available resources are: wood sawdust having a very low content of moisture coming from wood industry and wood waste obtained by the maintenance operations of the forests and the urban green, that is supplied in form of pieces of tree and has a high moisture content.

A preliminary analysis of the business process showed that the wood waste is used mainly to manufacture wood chips, while pellets are just manufactured from sawdust. As shown in Table 1, the yearly availability of the wood coming from sawmills is smaller than the amount coming from forest and urban management. Actually the business process related to the production of woody fuels is able to satisfy the market request of wood chips, while a big deal of pellets market demand is still unmet.

Pellet production therefore constitutes a relevant case study to demonstrate the applicability of the methodology developed by the authors in the context of under- capacities.

Each step of the method summarized in the previous section is presented in details hereafter.

4.1 Building the Model of the Current Business Process

The IDEF0 model of the manufacturing process is shown in Fig. 1. The system modelling determines the segmentation of the process in six phases: A1 Trituration, A2 Purification, A3 Dewatering, A4 (second) Trituration, A5 Pelletizing, A6 Cooling and packaging.

According to Fig. 1, the process used to produce the wood chips starts with the trituration (called "chipping") of the wood biomass in order to obtain chips having overall size of less than 30 × 30 × 30 mm. The next phase is aimed at purifying the obtained wood chips by removing any kind of impurities (such as solid particles, glass, iron, etc.). In order to avoid fermentation, the moisture content is reduced to 20% in weight: dewatering is performed using thermal heating and at the end of the process the wood chips are cooled in air. In the next phase the wood chips are further triturated up to the size of the sawdust for the pelletizing phase. The pelletizing of the sawdust produces a not negligible heat due to the high friction of the extrusion die, thus the pellets require to be cooled at the end of the process before the final packaging.

The resources to make the system work properly range from energy to labour and space occupied by tools and machinery. In Table 2, the power consumption of each phase of the process is surveyed. The dewatering phase requires a high energy consumption in order to reduce the moisture content of wood chips from 50 to 20% in weight, the thermal process usually requires 3600 MJ for each ton of removed water. Also different relevant resources are indicated in the same Table, that shows that the pelletizing is accounted to a large involvement of human skills in terms of labour, experience and know how, while the machines addressed to perform the dewatering stage show the largest size.

As shown in the IDEF0 diagram (Fig. 1) there are some output flows of energy wasted from several phases of the process that constitute unexploited internal resources of the system (such as: the heat content discharged by the cooling phases, the heat content of the air ejected from the dewatering furnace, etc.) as well as the materials extracted by the purification process and the water obtained during the dewatering operations. While the materials extracted by the purification phase may constitute market opportunities, the thermal flows discharged during the process show temperatures that don't allow their convenient recycle for other tasks of the process.

4.2 Identifying the Benefits and the Performance of the Process

In the current business process, the set of the critical features to access market is constituted by five requirements. A suitable lower heating value, LHV (CR1), represents the main performance of wood pellets, since it is intended to deliver the main function of providing heat; this attribute holds the biggest importance and the correspondent relevance degree is 5. The sector experts have accounted with an importance level equal to 3 some characteristics of the product referred to the licensing laws, such as size (CR2), hardness (CR3) and brightness (CR4). At last the availability of wood pellets in bags (CR5) represents a further attribute for the manufacturing process, but it is accounted for a minimal degree of relevance (thus, 1). Table 3 summarizes the requirements and their relative importance.

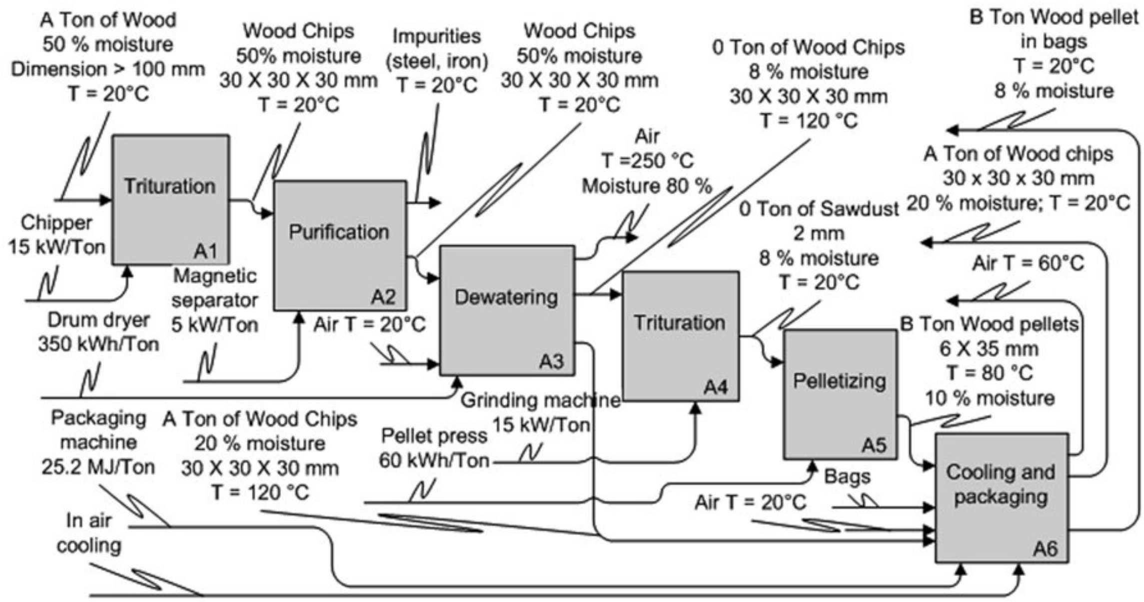

Fig. 1 IDEF0 model for wood pellet manufacturing from renewable wood

Table 2 Resources consumption for each phase of the process

Phase	A1	A2	A3	A4	A5	A6
Energy consumption (MJ/Ton)	54	18	1260	216	25.2	0
Personnel involvement (labour hours/Ton)	0.1	0.1	0.3	0.1	0.5	0.3
Space consumption (plant portion)	0.1	0.2	0.35	0.1	0.1	0.15

Table 3 Wood pellets attributes and their accounted relevance

Attribute	R_i
CR1 – LHV	5
CR2 – Size	3
CR3 – Hardness	3
CR4 – Brightness	3
CR5 – Availability in bags	1

4.3 Identifying the Phases' Extent in Generating Benefits

As the methodological section describes, the phases' extent to generate satisfactory products is evaluated through the introduction of k_{ij} coefficients. Such coefficients are assessed by process meta-experts.

The estimation of the k_{ij} indexes takes in consideration that the most relevant CR (lower heating value), is determined mainly by the dewatering phase, while the first trituration phase gives a minor contribution. The assessment can be explained through the parameters influencing the performances of the dewatering process based on thermal heating (quantity of the evaporated water and the productivity): dimensions of the raw material at the inlet of the furnace and temperature of the process. CR2 (Size), CR3 (Hardness), CR4 (Brightness) are determined mainly by pelletizing since in this phase the sawdust is pressed and shaped up to the dimensions of the pellet. CR5 (Availability in bags) depends mostly on packaging and on the size of the pellet, determined by the pelletizing and the second trituration.

Table 4 summarizes k_{ij} coefficients, while Table 5 shows the calculation of POS_j indexes through (Eq. (1)), thanks to the values of Ri shown in Table 3.

Table 4 Contribution of wood pellet production phases to fulfil the system requirements

Phase	CR1	CR2	CR3	CR4	CR5
A1	0.4	0.1	0.0	0.0	0.0
A2	0.0	0.0	0.1	0.2	0.0
A3	0.6	0.0	0.0	0.0	0.0
A4	0.0	0.2	0.0	0.0	0.0
A5	0.0	0.7	0.9	0.8	0.1
A6	0.0	0.0	0.0	0.0	0.9

Table 5 Accounted satisfaction (POS indexes) arising from each phase of wood pellet manufacturing process

Phase	POS_j
A1 – Trituration	2.30
A2 – Purification	0.90
A3 – Dewatering	3.00
A4 – Trituration	0.60
A5 – Pelletizing	7.30
A6 – Cooling and packaging	0.90

Table 6 Overall value POV_j of each production phase, estimated as the ratio between the contribution to the customer perceived value (POS_j) and the resources consumption. Energy, labour and space resources have been determined according to Eqs. (3), (4) and (5) and are expressed in €/ton; in grey the most critical process phase

Phase	POS_j	Energy	Labour	Space	POV_j (%)
A1	2.3	3.0	2.0	1.0	31.7
A2	0.9	2.0	2.0	2.0	12.4
A3	3.0	38.0	6.0	3.5	5.2
A4	0.7	3.0	2.0	1.0	8.3
A5	7.3	11.0	10.0	1.0	27.5
A6	0.8	1.5	2.0	1.5	14.9

4.4 Determining the Overall Value of the Process Phases

The study of the business process has highlighted the main resources involved in the system.

The time to market doesn't represent a critical factor for the analyzed business process; moreover, the manufacturing of pellets from wood waste doesn't show remarkably longer times than their traditional production from sawdust. Thus the duration of the production phases is not considered relevant for the examined value creation process, as well as the undesired effects of the manufacturing phases (e.g. noise, vibrations, maintenance, etc), that aren't actually pointed out.

Therefore the phases' value estimation has neglected operating times and drawbacks, focusing the attention just on the employed resources. In other terms, the coefficients c, t and h don't play any role in this specific case study.

The resources consumption has been normalized assuming a reference production of 1 ton of pellet from renewable wood. More specifically, the analysis has included the expenditures for energy, labour and space occupied by the plant. The costs related to the acquisition of the necessary quantity of wood to produce 1 ton of wood pellets have been neglected since such kind of biomass is still considered as waste and currently it doesn't possess any economic value. The energy costs have been calculated with reference to the consumption of each phase in the treatment of 1 ton of wood pellets and to the current price of the electric power. The expenditures accounted to the labour for each phase have been calculated through the accounted involvement of the personnel in the production of 1 ton of wood pellets and the hourly cost of the employed workers. The costs involved for the space occupied by the plant have been calculated dividing the monthly amount of real estate expenditures for the industrial site by the potential production of the plant in the same period, in terms of tons of wood pellets. Then, such expenditures have been split to calculate the amount accounted to each process step taking into consideration the ratio of the space occupied by the machinery utilized to perform the phases.

Thus, the expenditure values have been calculated through the following Eqs. (3), (4) and (5).

$$\text{Energy expenditure} = \text{phase required energy for processing 1 ton of pellet} \times \text{electric power cost} \tag{3}$$

$$\text{Labour expenditure} = \text{employed labour for the phase} \times \text{hourly labour cost index} \tag{4}$$

$$\text{Space expenditure} = \text{ratio of the space occupation for the phase machinery} \times \text{monthly real estate expenditure/number of 1 ton batches of pellet potentially produced in a month} \tag{5}$$

Table 6 shows the results of estimated expenditures for the exploited resources and the phases overall values POV_j, consequently calculated through (Eq. (2)) and subsequently normalized in order to obtain a percentage score.

4.5 Prioritizing the Directions for Improvement

As shown in Table 6, the dewatering task (A3) has the smallest POV index, thus it represents the most critical phase of the business process, since its contribution to the creation of the value of the product, compared with the other phases of the same manufacturing process, is not proportioned to its consumption of resources.

Similarly, the second trituration phase (A4) seems to present critical issues.

A more detailed analysis of the process, performed on the basis of the above mentioned results, reveals that some important limits of the production process of pellet starting from wood waste are due to technologies that are not able to treat, in an efficient way, biomass having a high moisture content.

In order to obtain pellet with a high energetic yield, the moisture content in the green biomass (approximately 50% in weight) must be drastically reduced. The technologies based on thermal dewatering use rotating or fluid bed furnaces that are fed by methane, oils, or a part of the raw biomass. This involves high fuel consumption, due to the meaningful amount of water that should be extracted. The efficiency of the dewatering phase could be strongly improved if the size of the biomass could be reduced at the inlet of the furnaces but unfortunately current systems for wood trituration are not able to treat biomass having a high moisture content. Moreover the pressing technologies used for the pelletizing of the sawdust are not able to dewater the biomass.

The analysis performed so far suggests improvements of dewatering and second trituration phases by developing convenient manufacturing technologies for wood pellet production. The goal is to obtain wood pellets capable to satisfy the CRs, using wood waste coming from forest and urban green maintenance. In such a way the pellet market demand could be totally satisfied thanks to a more rational exploitation of the available biomass resources.

5 Discussion and Conclusions

The analysis of the scientific and technical literature in the field of renewable energy confirms that the drying and the trituration of the woody biomass are critical phases in the production process of pellet starting from green wood. In [32, 33] it is clearly explained that the drying process based on thermal heating has a not negligible impact on both quality and production costs of wood pellet and new drying systems should be developed in order to make more efficient the pellet manufacturing process in terms of energy consumption and product characteristics delivered to the final customer. In [34] it is claimed that in wood manufacturing industry, drying is considered the most relevant matter determining problems in process controllability and high energy expenditures. Several studies have been carried out and several technologies have been introduced to improve this phase in wood industry, as it is summarized in [35]. Furthermore, previous researches performed by the authors aimed at identifying the constraints of the pellet production process in terms of throughput, has led to individuate the trituration and dewatering phases as process bottlenecks [36].

The aforementioned researches and several others, widely confirm the results obtained by the application of the proposed Process Value Analysis. Such evidence provides a positive feedback for the applicability of the proposed methodology for re-engineering activities of business process experiencing under capacities in satisfying the product market demand.

The proposed method allows the identification of the critical process phases on the basis of the evaluation of their impact in determining the customer perceived value of the product attributes. This evaluation also takes into account all the resources each phase involves in order to guarantee such attributes.

As stated in Sect. 1 the Process Value Analysis has demonstrated its efficiency in business process re-engineering tasks mainly related to well established processes needing to preserve the competitiveness of the delivered products/services in a crowded marketplace. In this chapter its applicability to another class of problems concerning under development processes not able to satisfy the market demand, whereas the customer requirements are described by a set of goal attributes to be performed in order to access the market. In this specific case the test has been carried for a business process with poor performances, which consequently don't allow the complete exploitation of both the available resources, and the market demand.

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Decision Making and Value Considerations During the Early Stages of Engineering Design

G. Medyna and E. Coatanéa

Abstract Early design is a critical stage in product and service development. The choices made during this period influence the final spread and acceptance of the artifact and therefore must be made in the best possible manner. Different aspects must be taken into account during decision making such as value, risk awareness, environmental impacts, etc. The present work studies value in engineering projects using dimensional analysis and its integration in the decision making framework while putting an accent on value considerations.

Keywords Value · Decision making · Dimensional analysis · Early design

1 Introduction

The first stages of engineering design are crucial for the final product or service. The choices made during the early design stages greatly influence the final cost, representing up to 70% of it [1]. Historically, the final performance of a product was achieved through trial-and-error [2] which is time consuming and all possibilities cannot be assessed through such methods.

The work presented in this chapter is part of a larger project which aims at facilitating the decision making process during the early design stages which takes into account such aspects as risk awareness, value, environmental impact, etc. The novelty of the work resides in the use of dimensional analysis and dimensionless numbers in order to objectively compare and rank design options.

This chapter presents the notion of value efficiency. The notion of value efficiency is important for engineering projects as their viability largely depends on their feasibility as well as on the income they can generate. The proposed methods for measuring value efficiency rely on $\prod$ dimensionless numbers created through dimensional analysis. Dimensionless numbers are commonly used in physical representations yet dimensional analysis can also be applied to economical aspects. The use of dimensionless numbers allows for an easier comparison of models when number to number comparisons are impossible or impractical.

This work is constituted as follows:

The second part presents the state of the art of decision making in engineering design and specifically value considerations. The third section includes a presentation of the decision making model used and the dimensionless numbers developed for value efficiency. The final section includes a discussion on the proposed methods and conclusions.

2 Decision Making in Engineering Design

Engineering design is a complex process which has been described as majorly relying on creativity, analysis, problem solving and so on [3]. Multiple approaches can be taken towards engineering design, [4], for example, suggests viewing it as a decision-making process. The current work does not dwell on the exact definition of the design process but rather considers how to improve it. Methodologies for the early stages of design vary greatly from designer to designer and company to company. A designer's experience, but as well as education, plays a large role in the final outcome of the product [5]. For experienced designers it may be possible to achieve good results very early in the design having considered very few alternatives [6], yet some solutions may get overlooked. Given today's computer power, it is possible to make a great number of models and simulations but that is often time inefficient and resource consuming.

A review of literature related to design methodologies and decision making has been done by Ng [7]. Three major types of decision making aids are established, normative,

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descriptive and prescriptive, which revolve around step-oriented design methodologies. There are many shortcomings to most decision making aids and effective aids should perform the following functions:

- Allow designers to design in accordance to his or her preference or natural way
- Enable traceability of minor design decisions
- Easily link to the design requirements

Further recommendations are given about such aspects as the inclusion of the possibility of CAD modeling and time checking.

2.1 Decision Analysis and Making Model

Making decisions in engineering design is a hard task because one is not only faced with almost-limitless possibilities but one is also required to think about the interests of many actors, the company, the environment, human values, etc. [8]. Using a decision analysis approach can help a decision-maker, in this case the designer, assess the decisions to make with more objectivity. In order to provide the objectivity needed, valid measurements and metrics must be provided during the decision and design process [4]. Moreover, engineering design can never be reduced to a set of decisions with undisputable input data, human input is necessary for certain steps, the determination of appropriate metrics and description of major relevant relationships between parts, which can be subjective yet drastically limit the calculation time.

Different stages during an engineering project require decisions to be made. The focus of this research is the stage past the requirement specification, when alternatives must be presented to fulfill those requirements. Follows a representation of the decision making model proposed in order to choose the most suitable solution. Many different analysis processes can be found in the literature, the model in Fig. 1 is based on the framework provided by Clemen [9].

Below is a shot summary of the contents of the different stages:

Problem situation and understanding: careful identification of the decision problem as not to address the wrong problem

Alternatives generation: alternatives can be generated through creativity sessions for example. A good examination of the objectives to achieve can provide new alternatives which would not have been generated otherwise, hence the importance of the first step.

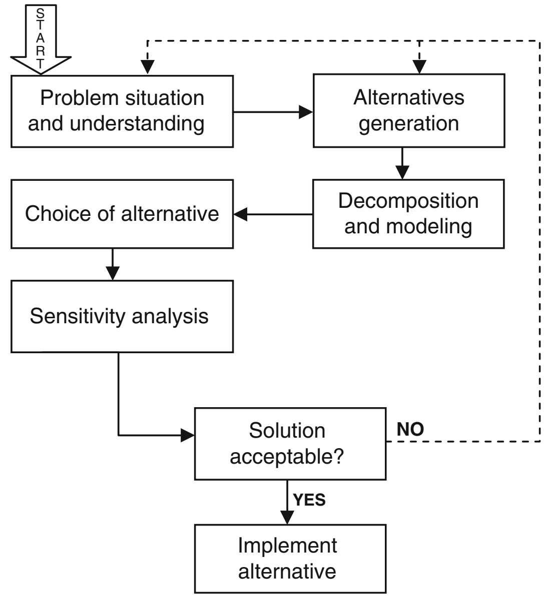

Fig. 1 Decision making model

Decomposition and modeling: the problem is decomposed into manageable parts and is modeled.

Choice of alternative: provided the model of the decision problem, the designer decides which is the best suited alternative.

Sensitivity analysis: sensitivity analysis performed on the system with the chosen alternative; is the chosen solution still the optimal one even with slight changes to the model? If not, perhaps there is an alternative which will respond well to slight variations in the model. This step is especially important when considering the whole system, a slight change to one component can result in drastically increased or decreased performances of other components.

Implementation of the chosen alternative: once the decision maker is satisfied with the chosen alternative, he or she can implement it.

The present article concerns the third stage of decomposing and modeling the problem in order to make the choice of which alternative is the best suited. There are many aspects that come into play during the modeling and the final aim of the current research project is to focus on three of them as described in the section below.

2.2 Choice Influencers

Many models for decision making have already been proposed for engineering projects but they generally only take into account one aspect of a project, as for example Kuo's "Green Fuzzy Design Analysis" (GFDA) which looks at environmental issues [10] which has limitations [3]. It has been proposed that the goal of engineering design can generally be reduced to making money and most relevant considerations can be transformed into equivalents of monetary units in order avoid multi-attribute problems [4]. The goal of our current research is to tackle several aspects which have great importance during the decision making process. The three choice influencers below are presented in the order of development during the research project.

2.2.1 Environmental Impacts

Environmental aspects of new products and services are an important factor for many companies and research groups as societies and governments call for more environmentally conscious solutions [11]. The method proposed to assess environmental impacts uses the notion of exergy, useful energy, and was developed by [12] and later further studied by [13] and [14]. This aspect is assessed using dimensional analysis and was the starting point for the development of dimensional numbers outside the scope of environmental studies and physical units. The basics of dimensional analysis are presented in Sect. 3.1. Three Π numbers related to exergy and environmental aspects have been created, the efficiency of use of resources, the efficiency of primary exergy conversion and an environmental impact number.

2.2.2 Value Considerations

The development of new projects relies heavily on monetary input. Projects are expected to generate value [15], this value is not necessarily expressed in monetary form, it can also be as improvement in company image for example. In the case of sailing teams, which participate in such races as Vendée Globe, successful new projects result in a well placed boat which receives press and television coverage and therefore shows off the names of sponsors. This in turn pleases the sponsors who, in most cases, choose to continue the sponsorship.

In engineering projects, value is closely linked to physical properties of the different components. Using dimensional analysis, it is possible to link the economical and physical aspects and provide information for simulations and comparisons. Section 3.2 provides details of the calculations.

2.2.3 Risk Awareness

Engineering projects contain a certain amount of uncertainty and the actors linked to a project all have different risk awareness towards that project. Risk is a complex aspect which has physical, monetary, cultural and social facets [16]. As all the actors have different backgrounds, their risk perception will be different. For example, the project leader can choose and develop an extremely daring solution which has a low slim chance of succeeding on the market, yet the solution is rejected because it does not fit with the company's investment plans which give priority to small incremental innovative solutions. Therefore the time spent developing the rejected solution can be considered as wasted. Capturing the different levels of risk awareness from the start of the project and taken them into account during the decision making process would limit possible rejection of proposed solutions by one of the actors.

Risk awareness has not been yet incorporated into the presented decision-making model. Future work will include a study the necessity of dimensionless numbers linked to risk and potentially the creation of such numbers.

3 Value Considerations in Decision Making

3.1 Dimensionless Analysis

The different aspects mentioned above are not measured with the same units and therefore cannot be compared number to number. In order to facilitate comparisons and understanding, we propose the use of dimensional analysis and dimensionless numbers.

In physics, dimensionless numbers are often used to describe phenomena such as fluid flow, for example with Reynolds number. The creation and use of those dimensionless numbers is based on Buckingham's $\prod$ theorem [17, 18].

In economics, dimensional analysis is often used to describe monetary evolutions over a length of time which leads to numbers with units measured in time. Dimensionless numbers are less commonly used than in physics, nevertheless, they exist. For example, economic elasticity is expressed with a dimensionless number.

Dimensional analysis relies on the transformation of design space which uses multiple metrics into a topological space called "metric space" which uses one metric, the dimensionless number. The complete definition of a metric space can be found in Bourbaki [19]. A key aspect of dimensional analysis using Π numbers is the possibility of interaction between variables, either inside a single Π number or between different Π numbers. The study of these interactions allows for a better simulation of a model.

3.2 Value Model for Engineering Projects

In order to comprehend the link between decision-making in engineering projects and value, two approaches have been developed. Potentially only one or both can be useful to fully describe the economic side of projects. In the future, case studies will be performed in order to assess the methods.

3.2.1 "Input/Output" Economic Approach

Engineering projects are made up of multiple parts. The first approach to study value presented first considers each part separately [20].

The general dimensionless number created through this approach is of the form (Eq. (1)):

$$\Pi_i = \frac{\text{monetary output}}{\text{monetary input}} \quad (1)$$

The total dimension for both the monetary input and output is a monetary unit such as the euro or dollar. The units of individual component of the dividend and divisor must not all be monetary units.

The monetary output is different for each part and is calculated as follows in Eq. (2):

$$\text{monetary output}_i = G_i(I_{sal} + I_{oth} - E_{mar} - E_{oth}) \quad (2)$$

where:

I_{sal} : final sale price/income,
I_{oth}: other types of income (e.g. positive image increase),
E_{mar}: marketing expenditures,
E_{oth} : other global expenditures (e.g. logistics),
G_i : importance of part in project

Incomes are positive values, as money is spent on expenditures they are subtracted in the equation.

The last value should be of less than 1 for all parts and the total should add up to 1. A priori, all parts should have equal importance. If the designer chooses to, he or she can set specific value for G_i. For example if the part is crucial for the functioning of the product, the value of G_i will be important whereas if the part has more of an aesthetic value, G_i would be closer to 0.

The monetary input it linked to physical data such as the materials needed and the work required to provide the final product. In order to facilitate the calculations, data linked to marketing and promotion is not considered.

Equation (3) shows an example of the different components which can be found in a $\prod$ number:

$$\Pi_i = \frac{(I_{sal} - E_{mar} - E_{oth}) \times G_i}{W_{hrs} \times P_{hrs} + \sum(Q^1_{mar} \times P^1_{mar})} \quad (3)$$

where:

I_{sal} , E_{mar}, E_{oth} and G_i are as above,
W_{hrs} : work hours,
P_{hrs}: hourly wage,
Q^i_{mat}: quantity of material needed,
P^i_{mat}: price of material.

All the $\prod$ numbers created represent the efficiency in terms of value of the parts considered.

If $\prod$ is largely greater than 1, the part creates great income for the company.

If $\prod$ is close to 1, the company is neither losing nor making profit on the part.

If $\prod$ is largely inferior to 1, the company is not making any profit on the part and perhaps a new study should be done to see if the value efficiency of the part cannot be increased.

As the $\prod$ numbers are dimensionless, they can be multiplied to represent the whole product following the product law. A proposal for the combination of multiple Π numbers from different organs has been presented in [13]. This allows an easy estimation of the whole value efficiency of the project, the greater the final $\prod$, the greater the value efficiency. Such an efficiency study can then be used to compare multiple projects or alternatives inside a project during stage 3 in the decision making model.

Though facilitating comparisons and aiding the decision making process, the proposed method contains a number of shortcomings. First of all, some of the data needed may be erroneous as it is to be estimated before the final sales, such as P_{sal} for example. Should the product not sell, the number of unsold items will diminish the income per item produced. This can be taken into account in E_{oth} but it can hardly be predicted before the sales happen. Moreover, more error can be introduced through the estimation of G_i if the proper weighing method is not used. Nevertheless, it is a starting point to the feasible inclusion of an economic aspect in the early design stage.

3.2.2 Economic Drivers in Value Consideration

Each aspect of a project can be described from a physical point of view, the key of this approach is to link the economical and physical worlds. All physical components will not have the same monetary impacts; the ones with the highest impact are considered cost drivers.

These cost drivers are measured by the cost of providing a given amount of the material or product. The units for this measure are [cost]/[physical units]. Each aspect is then described through a dimensionless number as in Eq. (4):

$$\Pi_i = \frac{[cost]/[physicalunits\,\mathrm{i}]}{[totalcost]/[compphysicalunits]} \quad (4)$$

For example, if the project requires plastic tubes, the costs associated with those tubes would be:

- Material cost
- Manufacturing cost
- Logistics cost
- Recycling cost
- Other majors linked costs

The costs are estimated per appropriate physical unit, in the case of tube it is length therefore the final expression is in [cost]/[meter].

Having constructed representations for all the cost drivers, it is then possible to estimate the complete monetary impact of the project. The second approach is complementary to the first one and will be further developed through case studies.

4 Conclusion – Discussion

The present work aims at facilitating the decision making process during the early stages of engineering design. Value considerations are essential during the decision process as companies and research group aim at generating value and remaining competitive. The use of dimensional analysis and dimensionless numbers allows for an easier comparison and scaling inside and of engineering projects.

There is a need for decision making aids for the design process and there are multiple options for these aids which already exist, but they present shortcomings such as a lack of integration with software which engineers use or a lack of integration with the designers' methods. The dimensional analysis method only considers three choice influencers, for the moment, but it is possible to envision the development of other aspects if the method is deemed viable and appropriate.

As presented previously, the project of a decision making aid tool for early design is ambitious and encompasses multiple facets. While the general mainframe for decision making has been defined and dimensionless numbers have been defined for environmental impact as well as value considerations, risk awareness will be the subject of future work. Moreover, case studies will be performed for the proposed dimensionless numbers linked to value considerations. Following the completion of the work on the three facets mentioned above, a large scale case study will take place to evaluate the decision making framework.

It is mentioned in Sect. 2 that CAD integration is highly recommended for decision tools for engineering projects. Future work will include the development of software based on the research in order to facilitate its implementation. Given the small amount of data required for the proposed method of dimensional analysis, integration with existing modeling software is possible. An important goal of the software will be to provide a graphical representation of the results to facilitate understanding and comparisons. An interesting graphical representation which could fit Π numbers can be found in [21].

For the moment the work only concerns aspects after the systems requirements have been set. As the research is done in a research group with members who focus on the requirement definition stage, a link with even earlier phases of the design process is planned.

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Product Design for Global Production

G. Lanza and S. Weiler

Abstract A global set-up of production sites and suppliers in an increasingly globalised world provides huge opportunities for companies, such as the development of new markets or the reduction of production costs. In spite of these advantages and the desire of companies to make full use of them, global production has not been mastered so far and its potential has not yet been fully tapped. Global production often results in quality issues or unexpectedly high costs. The technical features of the product to be manufactured have a major impact on whether global production will be successful or not. This chapter aims at presenting an approach to tapping the potential of low-cost countries by tailoring product design to local needs and, at the same time, to reducing entrepreneurial risks.

Keywords Design for X · Global production · Global design · Product design adaptation

1 Introduction

Despite globalisation covering ever more areas, the product design centres of German multinational companies are still located at their domestic sites [1]. Purchase, production and sales, however, often have a global footprint [2]. Production sites and suppliers in particular are positioned globally at strategic locations. This enables companies to fully harness the potential of local advantages, such as low factor costs, access to knowledge or the domestic sales market [3]. Research shows, however, that companies often do not make full use of local assets which thus do not have positive effects on company profits [4]. Tapping the full potential of production sites in low-cost countries offering a huge savings potential as a result of low factor costs such as labour, energy or equipment costs represents a particular challenge for German companies: Costs are higher than initially expected, products show poor quality or cannot be manufactured at all, product piracy and late deliveries or supply bottlenecks figure among those difficulties that occur in global production (Fig. 1).

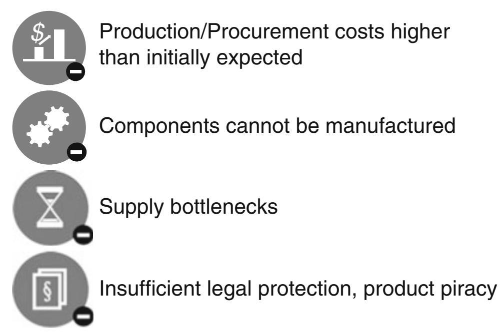

Fig. 1 Major challenges of global production

2 Opportunities of Localised Product Design

The challenges and problems in global production mentioned above often correlate with the design of the product to be manufactured globally. Product designers do not sufficiently take into account the characteristics of different production sites and the impact a global value-added chain can have as these factors are often unknown to them. Components are often adapted to the state-of-the-art technology at the domestic site and thus can show a very high level of complexity [1]. In Germany, the automation of manufacturing processes is considered to be a reliable approach to reducing costs while maintaining a high level of quality. Products are designed respectively to meet these manufacturing standards [5–7]. This paradigm is one of the reasons why production transfers to low-cost countries and low-cost country sourcing often lead to or even fail due to unexpectedly high costs and/or poor product quality since certain components cannot be manufactured at low-cost production sites. The Institute

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of Production Science (wbk) developed a method to adapt product design to the local production environment which provides product designers with a tool to tap the advantages and seize the opportunities of global production [8, 9]. Comparative advantages can be fully tapped and considerable savings potentials realised if product design is localised. Furthermore, an adapted design can enhance delivery ability and flexibility, improve product quality by adapting the component to the local manufacturing environment and prevent product piracy and high coordination costs as a result of a targeted product modularisation. If local influencing production factors are taken into account as early as during the product design phase, the end product will show high quality without incurring additional costs.

3 Global Production Factors

A deep understanding and assessment of the local production environment is a precondition to successfully adapting product design to the local manufacturing conditions. These can then provide the groundwork for specifying the requirements to local product design. The Institute of Production Science (wbk) identified the essential local influencing factors to develop methods to facilitate these processes. The following nine basic global production factors were identified:

3.1 Factor Costs

The production costs of a product are determined by the amount and price of resources used. The local prices of manufacturing resources therefore have a major impact on the costs of the manufactured goods.

3.1.1 Labour Costs

In 2007, labour costs per hour of assembly work varied from $1 in India to $37 in Germany [2]. These enormous global differences in labour costs mainly result from the varying degree of economic development and non-wage labour costs differing locally. If different production sites shall be compared with regards to labour costs, the productivity of the respective location needs to be taken into consideration as well though.

3.1.2 Machine Costs

If locally available machines are used, machine costs vary considerably in different locations. The machine hourly rates for Chinese injection moulding machines and dryers, for example, are about 80% lower than those of German hourly rates [10]. Differing machine hourly rates can be mainly traced back to varying machine procurement costs, to different occupancy and maintenance costs and net machine running times.

3.1.3 Material Costs

The prices for standardised pre-manufactured products and raw material differ considerably in different locations, partly by a factor of ten [1]. The main reasons for this are, on the one hand, the natural resource availability of ores, for example, and, on the other hand, state market interventions [1].

3.1.4 Energy Costs

Different energy prices, like material prices, mainly result from their availability on the market as well as state regulations. The prices for electricity and fossil fuels on the Russian market for example only account for a small fraction of energy prices in other countries [1]. This global production factor plays a major role in energy-intensive manufacturing processes.

3.1.5 Capital Cost

Investment in manufacturing equipment, long distance transportation and huge warehouse stocks lock up capital and therefore lead to capital cost which can differ considerably in different locations as a result of the financial risk incurred.

3.2 Means of Production and Manufacturing Technology

Production equipment, machines and tools differ globally with regards to accuracy, machine reliability, meeting quality standards and the level of automation. The more complex and the higher the level of automation with regards to means of production, the better qualified machine operators need to be.

3.3 Employee Qualification

Staff worldwide show considerable differences in their level of education and qualification. The level of vocational training and qualification in low-cost countries is in general lower than that of high-wage countries.

3.4 Logistics Infrastructure and Routes of Transportation

Global production being distributed along the value-added chain requires land, water and air transport of products. The means of transport depends on the type and quality of logistics infrastructure as well as on product features such as value density, weight and volume. The risk of damage, loss and theft increases as a result of poor logistics infrastructure, difficult transport conditions and the frequent movement of goods.

3.5 Tariffs and Taxes

In cross-border production networks additional costs are incurred as a result of customs duties and taxes which differ from country to country. Product design may have a specific impact on the customs duties to be paid. For example, individual components are often taxed differently to assemblies or end products which results in products often being exported in parts before being assembled at the final destination. In addition to tariff measures, there are also non-tariff barriers such as import and export quotas which govern global production.

3.6 Cultural, Linguistic and Professional Background

Different cultural, linguistic and professional backgrounds often pose an obstacle to global cooperation [11]. Unfamiliar legal and working practices, a different understanding of quality as well as various different educational systems or technical standards lead to misunderstandings. This unfamiliarity therefore turns most low-cost countries into highly complex working environments for Western companies.

3.7 Global Coordination and Support

Global production sites and the associated long distances increase coordination, communication and support costs. This cost is also increased as a result of different cultural, linguistic and professional backgrounds as well as different stages of development. For example, low-cost country sourcing often requires supplier development in order to achieve the desired quality.

3.8 Legal Protection, Product Piracy and Knowledge Drain

Production in different countries takes place within different legal systems. In particular, the protection of intellectual property is a problem in many locations. Knowledge drain results from industrial espionage, product piracy or the sale of surplus production. In some locations the low level of staff loyalty and the resulting high level of employee turnover also facilitates knowledge drain.

3.9 Dynamic Development and Uncertainties

Global production factors are subject to changes and uncertainties. These are primarily caused by the complexity and expansion of the production network and the involvement of sites with a high level of political and economic dynamics. The economic enhancement of production sites leads to changes in global production factors, such as labour cost increases, amendments to legislation such as local content requirements or exchange rate movements.

4 Global Production Factors According to Their Importance and Location

Only a small number of new requirements need to be added to adapt a specific product design to a local production environment. What is more important is devising a new hierarchy of the requirements which have existed so far, mainly resulting in a slight shift of priorities.

Figure 2 shows six important production requirements which need to be taken into account to adapt product design to local conditions: required qualification and training of employees, use of capital, production equipment requirements, use of material, processing time and labour costs. The order in which they are listed corresponds to a typical set of priorities for large-scale manufacturing in high-wage countries. According to these principles, a higher level of material or capital use can easily be accepted if labour costs can be reduced [5]. The use of complex, capital-intensive manufacturing equipment which does not pose any problems at all if qualified and trained machine operators are available is supposed to reduce processing times and labour costs. Machine manufacturers and educational institutions are trying to meet the requirements of the manufacturing industries to provide highly-efficient manufacturing equipment and qualified and trained staff.

In low-cost countries priorities are typically quite the opposite. Since labour costs in low-cost countries are lower, the resource labour can be exploited to a greater extent.

Fig. 2 Product requirements according to their importance and location

This means that companies can forego a high level of automation in product manufacturing, which, in turn, reduces the production equipment requirements and the required level of staff training and qualification, as complex manufacturing equipment needs to be set-up, operated and serviced by experts. Another important point is the move to decide against using specialists as labour costs in general increase disproportionately with regards to the level of staff qualification (for example if expatriates are required). The use of material tends to be given a higher priority in low-cost countries. The relative share of material costs in overall manufacturing costs is usually higher since labour costs and machine hours for example are cheaper. Saving on material costs considerably reduces overall costs in relative terms. As far as machining and processing times are concerned, in low-cost countries too machine hourly rates and wages are based on the number of units produced. The longer the processing time, the higher the costs per unit are. Longer machining and processing times may be acceptable, however, in low-cost countries with lower labour and machine costs, if advantages arise in other areas, i.e. by using cheaper material.

The factors listed above can only be independently minimised in product design to a certain degree. Compromises may have to be made for everything reaching beyond these factors. The hierarchy serves as a guideline to reaching compromises on localised design. According to this hierarchy, a critical factor may be minimised if a factor of lower priority will, in exchange, be more extensively used. A compromise should, however, never be reached at the expense of a factor of higher priority. This hierarchy serves as a rough orientation. In order to optimise it, the concrete global production factors, e.g. factor costs, the qualification of staff members and the quality of production equipment at the respective location, need to be taken into account.

5 Product Design Requirements

Taking into account global production factors in product development leads to localised product design requirements (Fig. 3).

The targeted use of localised factor costs requires a design which is adapted accordingly. A product design is therefore

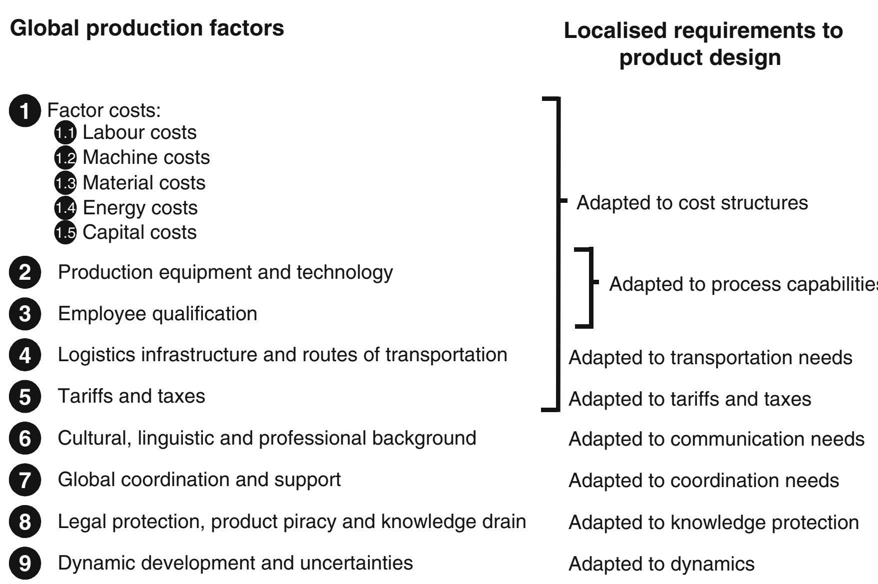

Fig. 3 Production site features become product development requirements

adapted to cost structures if favourable factor costs at the production site are intensively used and higher costs replaced by these. For example, a high level of manual labour is justified by low labour costs and makes it possible to save on machine costs by using simpler production equipment. Labour costs can also substitute material costs. For example, several components can be assembled manually instead of machining individual components from a single block of material. While this latter method may save on labour costs, the material wastage is greater. Furthermore, material and energy costs may result in products being designed at different production sites using a different manufacturing procedure.

A product design *which uses the process capabilities available* is characterised by two key features. On the one hand, it is tailored to the production equipment and technology available at the production site. If, for example, the precision and reliability of local production equipment are lower than at the domestic production site, the requirements in terms of production equipment used in the design should also be proportionally lower. A high level of requirements, in terms of production equipment, otherwise results in a potential failure to maintain quality or the accrual of disproportionately high costs owing to the import of requisite production equipment. On the other hand, the design takes account of the local level of employee training by corresponding to the respective level of qualification. A product design which is adapted to the available process capabilities is, at the same time, adapted to the cost structure as locally available production equipment and workers can be used.

A product design which is *adapted to the local logistics infrastructure* aims at reducing costs, loss of time and the risk of damage resulting from product transportation. An optimised robust product design which is adapted to the respective local means of transportation (shipping, air freight etc.) can be achieved by taking constructive and organisational measures which, again, are taken into account as early as during the product design stage. In order to use standardised carriers for transportation, product design must follow these standard dimensions. Storage and carrying costs may be reduced by decreasing the amount of manufactured components. Product design may influence this value by using identical parts and a favourable product structure.

A product design which is *adapted to tariffs and taxes* minimises customs duties and taxes. For example, this may be achieved by modularising the product which would enable value-added to be allocated suitably within the production network. Product assembling and procurement can also have an impact on tariffs and taxes.

A deep understanding of Western and international standards cannot always be taken for granted. A product design which is *adapted to communication needs* aims at avoiding misunderstandings which result from a differing cultural, linguistic and professional background. This can, for example, be achieved by issuing explicit and easy to understand technical specifications and local standards and norms that were agreed on. This will ensure for a better communication.

A product design which is *adapted to coordination needs* aims at facilitating as easy a value-added chain as possible with a low level of coordination and support requirements. A suitable product structure in particular can contribute to this. For example, reducing the variety of material and processes used will decrease the amount of players involved which would then reduce the support and coordination costs.

If regions with a high risk of product piracy or a high level of staff turnover are part of the production network, measures need to be taken to ensure that the product design *meets requirements in terms of knowledge protection*. For example, knowledge drain can be reduced by segmenting the product into individual technological components which are manufactured at the domestic site and uncritical components which can be manufactured globally.

Dynamic developments and uncertainties of global production can be reduced by a product design which is *adapted to dynamics*. If, for example, uncertainties appear as to the long-term availability and price development of a certain material at a location, an alternative design can be devised using replacement material to ensure production with different materials or semi-finished parts at a competitive price.

A successful global production aims at taking into account all the local requirements. These are, on the one hand, dependent on the individual company network. On the other hand, these requirements may or even need to be given different importance, should conflicts arise. The following example illustrates the implementation of this method in practice.

6 Practical Example from Industry: Adapting Product Design for a Production in Asia

A sensor product serves as an example to show how product design may be adapted to manufacturing and assembling in Asia. The German company is a manufacturer of innovative sensors for industrial applications with a global footprint. It understood the importance of localised product design to create a successful high quality product. In close cooperation with the Institute of Production Science (wbk), possible design outlines for the new design of a sensor which is planned to be manufactured and sold in Asia were determined. The primary goal was to improve product quality for production in Asia and to reduce manufacturing costs by implementing a product design which is adapted to the cost structure.

The measures identified were classified according to the before mentioned local requirements (see Chap. 5):

Adapted to the cost structure: Since labour costs at Asian production sites are cheaper, it is reasonable to make an extensive use of labour while saving costs with regards to other, more cost-intensive factors. One way to do so at the future production site may be reducing the requirements to production means. Several possibilities were found to adapt product design to ensure that product design requirements on manufacturing equipment are reduced:

With regards to the production of sensors, two sensor circuit boards have so far been soldered in a costly, automated soldering process, posing very high demands on process management. The design could be adapted using cables to connect different components (Fig. 4). If components are soldered manually, expensive automated machines do not have to be used.

Manufacturing equipment requirements may further be reduced with regards to how product labels are applied (Fig. 5). In Germany this is done by pad printing or thermal transfer printing. With regards to the Asian sensors, the expensive printing process can be replaced by manually applying a stick-on product label. A little mark on the housing enables the label to be positioned with a high level of precision.

A third product design adaptation to the existing cost structure may be achieved by modifying the way in which two assemblies are joined. Since tolerances are a critical aspect in joining processes, assemblies have so far been joined using an automated caulking process.

An accurate, expensive workpiece feeding system is required to precisely position the two components. The cost structure may be optimised by creating a design which enables components to be joined by means of a manual press (Fig. 6).

Adapted to the available process capabilities: With precision machines and a highly qualified and experienced set of staff members the German company can manufacture high precision moulded parts and lenses which later allow for an exact positioning during assembly. A high level of precision in manufacturing and assembling is essential for the later functioning of the product.

An adapted product design is reasonable to avoid being forced to rely on the local competencies at the production site of the new sensor. By using a movable lens, the stringent requirements in terms of tolerance may be eased. By setting the lens manually high precision automated assembly equipment is no longer required (Fig. 7).

The state-of-the-art manufacturing equipment of the German company facilitates quality control by automatically analysing process data. As only few automated production equipment shall be used at the new production site of the sensor, quality control will be carried out visually by line workers using reference gauges (Fig. 8). Suitable inspection criteria shall therefore be exactly specified in product design.

By using many identical parts, the requirements with regards to the training and qualification of staff can be kept at a low level. This also reduces costs for training schemes. Furthermore, the Poka-yoke approach is planned for assembly steps in which errors can easily be made. The assembly of two polarising filters, which need to be positioned at right angles, can be facilitated by adapting their shapes in a way that makes it impossible to fix them the wrong way (Fig. 9).

Adapted to transportation needs: A minor role is allocated to transporting the finished sensor from the production site to the market. This results from a light weight and a low volume as well as from a production site close to the market. More importance, however, is attributed to supplier logistics. It is the aim to only use one local supplier for every group of material in order to reduce supplier logistics costs (Fig. 10).

Adapted to tariffs and taxes: The production network is devised specifically in such a way as to incur as few levies as possible. This does not lead to the necessity to change product design. The production site and the sales market are part of the same free trade agreement which enables them to not only export products but also to include suppliers of the sales market without having to pay levies.

Adapted to communication needs: In order to avoid difficulties resulting from cultural, linguistic and professional differences, local engineers are included in the process of production development as early as possible. They assist locals in drafting technical drawings, using common standards and assessing whether suppliers are qualified or not.

Adapted to coordination needs: As holds true for an adapted logistics network, a restricted supplier network means less coordination and support costs. Fewer suppliers for example mean less time and money spent on supplier qualification and certification (Fig. 11). This may also reduce

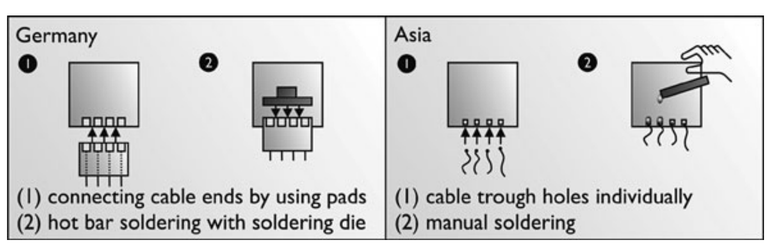

Fig. 4 Manual soldering replaces automated soldering

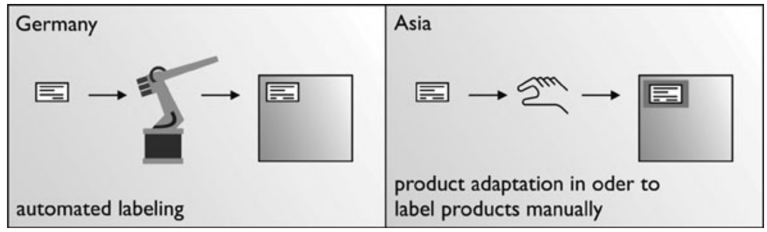

Fig. 5 Automated product labeling is replaced by manual product labeling

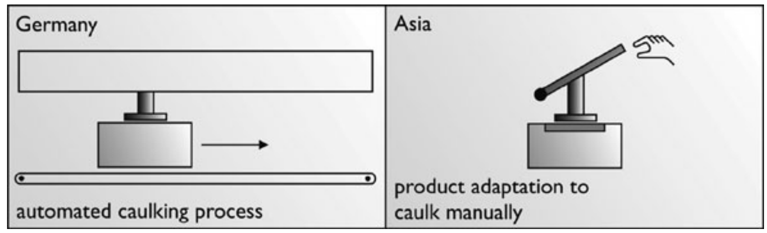

Fig. 6 Manual caulking replaces automated caulking processes

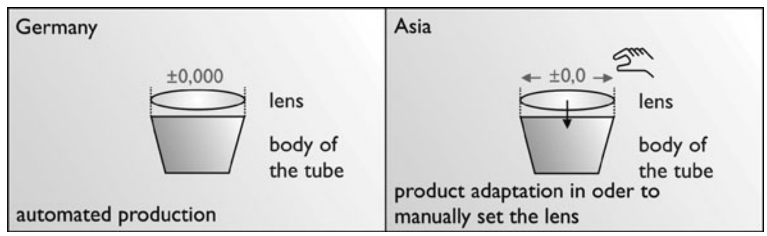

Fig. 7 Manual setting eases manufacturing tolerances

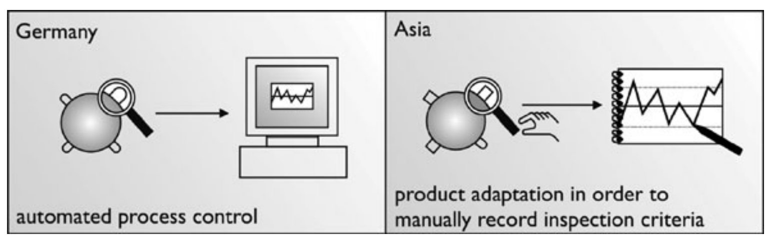

Fig. 8 Quality data must be able to be recorded manually

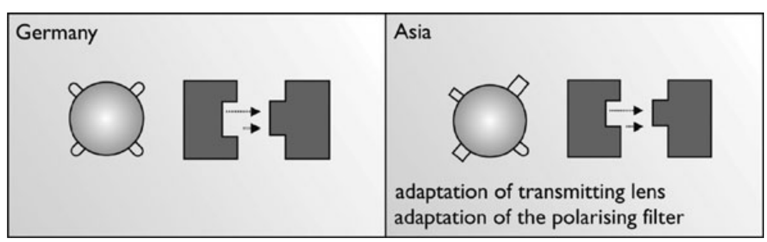

Fig. 9 An obvious asymmetric shape prevents errors in manual assembly

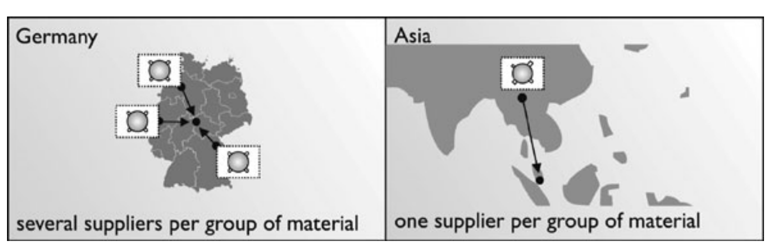

Fig. 10 Focus on only a few local suppliers slims supply chain

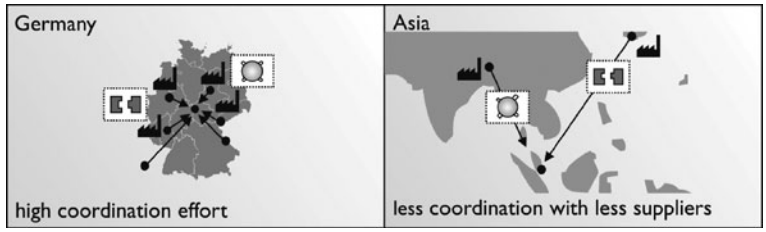

Fig. 11 One to two suppliers per group of material

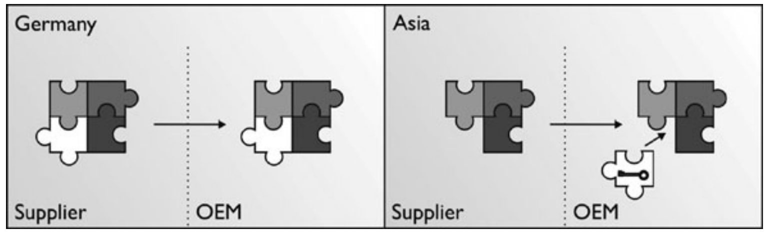

Fig. 12 Key components and their delivery in controlled volume reduces the risk of product piracy

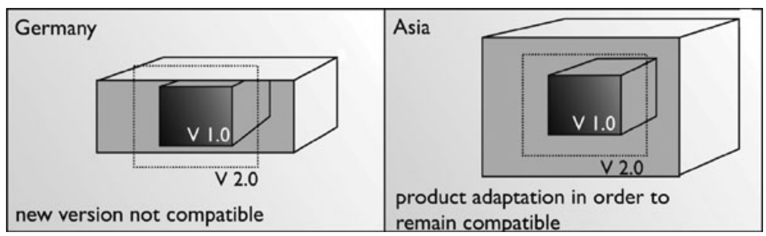

Fig. 13 Adapted to dynamic developments by foreseeing technical advances

travel costs and costs incurred by maintaining personal relations – a major aspect in Asian business relations. In order to implement these advantages, the materials and required manufacturing techniques used in product design need to be minimised so that few suppliers can cover the parts to be purchased for production.

Adapted to the requirements in terms of knowledge protection: By splitting the key technologies within a product, product piracy can be made considerably more difficult. A specific product structure tailored to the respective product helps achieving this (Fig. 12). The sensor logic represents its main innovation: It is placed on a chip which will continue to be produced in Germany. Only a specific number of chips will be delivered to the new production site in order to prevent misuse.

Adapted to dynamic developments: As the adaptation of production in a global production network leads to considerable costs, technological advances shall be taken into account in product design. It is foreseeable that the new chips of the next generation will require broader boards. To ensure that these chips will be continually used with the remainder of the components, the housing of this generation's products can be made bigger (Fig. 13). Moreover, a modular product structure provides the possibility to react flexibly to external changes.

7 Summary

In times of progressive globalisation and the onset of economic protectionism, global production will gain ever more importance. The success of multinational companies will depend on whether they take the global challenges of product development into account. The identified global production factors and the localised requirements resulting from them provide the basis for a methodological approach to supporting product design.

Local influencing factors at the production site were analysed and implemented as part of a practical application. The requirements to production, to the production network and to the product itself resulting from them were presented. This led to the development of critical measures which need to be taken in order to adapt product design to the local production environment within a global network.

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Systematic Preparation for Marketing a New Technology

W. Kästel

Abstract Innovations often depend on a new technology. Between the fully developed technology and the beginning of marketing efforts there exists a methodical gap. The utilization of the technology can vary about a lot of business lines, the market is totally unknown. In this case, a systematic methodology is essential to tell engineers and marketing people how to find additional application cases of the new technology in different business lines and prepare marketing activities. The result is a basis for drawing up a market analysis and a specification for a development project.

Keywords Innovation · Product design · Technology

1 Introduction

This chapter is about a new technology looking for its market. Normally the specification of a new technology applied in a new product is not yet established, because it depends on the utilization and the business line. There exists neither a specified product nor a market. A market analysis can not be designed. There is a methodical gap in the process of innovation. A methodology is needed for a successful introduction of the new technology in the market. A systematic approach would offer several advantages.

- A written documentation exists.
- Changes in requirement or conclusions will automatically be communicated between participants.
- nearly all options are considered.
- A systematic organization reduces complexity.
- The result is nearly independent from participants and staff changes.

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The proposal of this chapter may be regarded as a first approach to this topic, before more particular instruments are used for investigation, e.g. treatments of the Fraunhofer Institut IPA [1]. This analysis is dedicated to middle sized mechanical and electronic companies, which are producing products with their own development department. Perhaps, this concept will also work with bigger companies, but this has not been investigated.

The author has chosen the concept of innovation analogous to the OECD [2] proposal. Innovation is the creation of a new design or product which effects success for the company. It includes an invention element but also marketing efforts and finally a successful sale.

This model of the process of innovation is also used by Kästel [3]. In this approach the process of innovation can be subdivided into three phases. This makes it easier to analyse the individual elements of the complete process chain.

A description of the process of innovation according to Fig. 1 offers two advantages. First, it describes an a priori success factor for the enterprise. Second, it makes

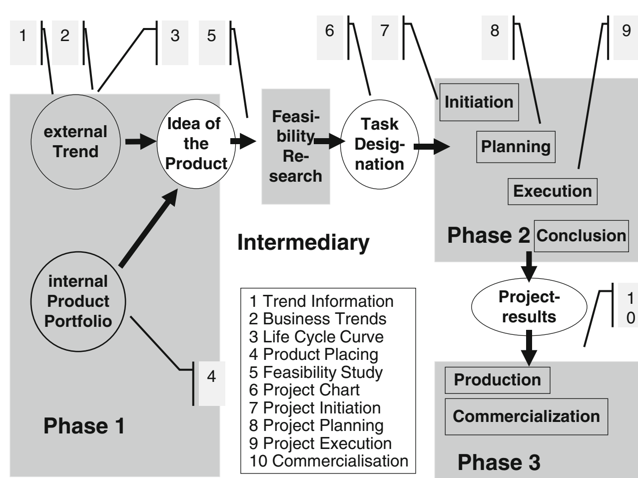

Fig. 1 Innovation process

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it easier to determine key financial data at every milestone. This structure has the advantage that it can easily be communicated within a business enterprise. The whole process contains marketing-, development- and sales-aspects handled by persons with considerably different points of view. It is important to find a general basis for communication. The used concepts are well understandable. There is a clear structure with two milestones. The three phases are:

1st phase: Idea of innovation: strategic product planning according to an existing trend
2nd phase: Innovation project
3rd phase: Production and marketing of the product

New technologies are launched in three totally different ways.

- Coming with an existing product to different markets.
- Replacement of an old technology by a new one in the same market.
- Using new features of a new technology in different markets

In this chapter the beginning of the whole process is described: trends, correlated with the internal product portfolio.

1.1 The Gap in the Process of Innovation

An enterprise possesses the know-how about a technology. The enterprise wants to open up a market with these products which it does not know yet. The aim of this effort is the assembly of a request list for a development project.

The classic way goes about the customer survey. This is a proven and successful method. But it is not sufficient to process the fields of application systematically and completely. A company does not have own customers in all lines of business. Frequently the marketing department is looking for application cases with the help of the field service. In this way there is no opportunity to find all potential customers. This situation is described in Fig. 2.

In the presentation a systematics for the preparation of marketing efforts is proposed to look for new applications with the help of the R+D – department.

Some authors look at marketing parameters at the same time without differentiating, if they depend on a new technology, e.g. Meißner in [4]. The well known innovation roadmap of Eversheim [5] could also be completed by this methodology.

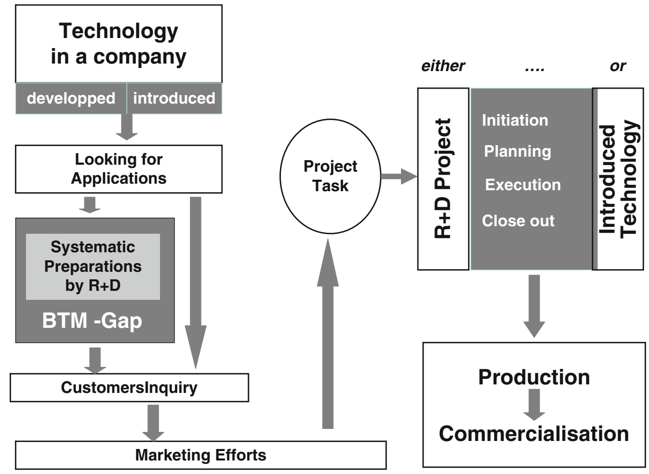


Fig. 2 Methodical gap in innovation management

2 Systematic Approach

Experienced managers are able to act on instinct to solve problems. They store behaviour patterns from accumulated experience. This filters out the appropriate solution. Particularly newcomers do not have these skills. It is advisable for them to proceed systematically.

As shown in Fig. 3, this concept proceeds in coordinated steps. They focus the process of innovation towards a decision. The aim is bridging the Technology Marketing Gap.

A systematic expiry follows these phases. A check list which demands decisions is situated at the end of every phase. The procedure leads to the promising application cases. These can be analysed with the well known methods like Quality Function Deployment, Value Engineering, Systematic Construction, KANO-Analysis. The final idea is a task for a feasibility study or a product development project. Some steps are explained as follows.

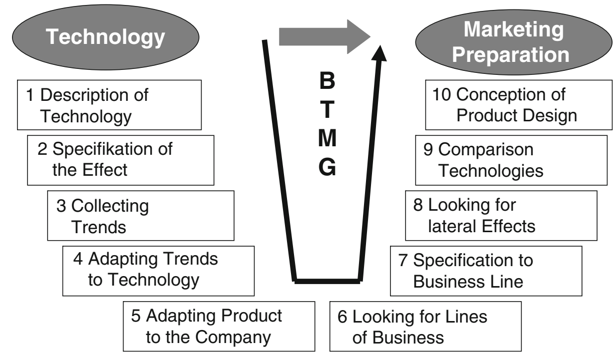


Fig. 3 Bridging the technology marketing gap

2.1 Collecting Trends

Before starting a product development project many primarily larger companies work with the instrument of the trend analysis. It offers several advantages.

- With this vocabulary the management experts and the engineers can communicate with each other.
- A trend is a hint, of what is going on in the market, a success factor for an innovation.

There is a lot of literature about trends, but rarely a quantitative description of the life cycle of trends. Horx delivers some monographs [6–8], also Häusel [9] and Haderlein [10] with an enumeration of the top 100 trends of today. Helpful is the use of forecast instruments like scenario technique [11] for the qualitative future prediction. Furthermore suitable are management tools like the interview of experts of a predicted Delphi [12] situation.

Table 1 delivers an example of regular trends for an enterprise of heating and air conditioning engineering in the environment of a new technology. The trend can be developed with the help of master mind methodology and judged roughly with a brainstorming method after strength and the interim progress of the trend (A extremely high, B medium, C weakly).

As a result a preselection follows for the further procedure. This is indicated in the last column. Looking for trends is therefore of importance because trends already give references to the sales argumentation of the product. A trend is a vision about the future behaviour of the market. It looks for things that are coming.

2.2 Adapting the Trend to the Technology and the Commercial Interest

The idea for a product develops out in two basic considerations. The first comes from the technical feasibility of a technological idea and the second from the consideration of what is in the interest of the enterprise. The new product needs to fit in the strategic planning of the portfolio. The enterprise has to prove the trends with consideration to the customers and the product portfolio. Even now the technological features for selling the product have to be developed. A rough outline describes the application. Information about this is obtained by literature, competitive products or best by an expert.

The example of the first step is continued in Table 2. The trend sensor integration is examined here for a manufacturer for printed resistances as an innovative product technology.

2.3 Quantification of the Life Cycle of the Trend

The urgency of the selected solutions has to be estimated and coordinated with the strategic development scenario of the company. It is necessary to determine, whether the enterprise would like to act as an innovation pioneer or as an innovation adopter. This happens throughout the life cycle curve of the trends. Surprisingly, this has a satisfactory effect that both, technical engineers and commercial managers, could estimate very well the elements of this curve, especially if the trend is already going on. An S-curve is based on the regulation points of this curve which are represented in Fig. 4. The time horizon has to be specified in accordance to the analyzed technology and the analyzed trend.

Table 1 List of trends

Trends for an enterprise heating and air conditioning

	Strength/priority	Selection
Deployment of flat monitors	A/A	
Computers with more power and storages	B/B	
Less oil and gas for heating facilities.	A/B	
Increase of the number of electronic devices in our buildings. Intelligent heating facilities.	B/B	
Scientainment: Sciens conqueres adventure culture (from /8/).	B/B	
Mood management: upgrowth of balance and good feeling (from /8/).	B/B	
Miniaturisation	B/B	x
Construction of modules	B/B	x
Sensorintegration	A/B	x
Digital circuits instead of analogue ones	A/A	x
Software instead of hardware	A/A	
Time saving in development and production	A/A	x
Improving reliability	A/A	x
Remote controlling	A/A	x

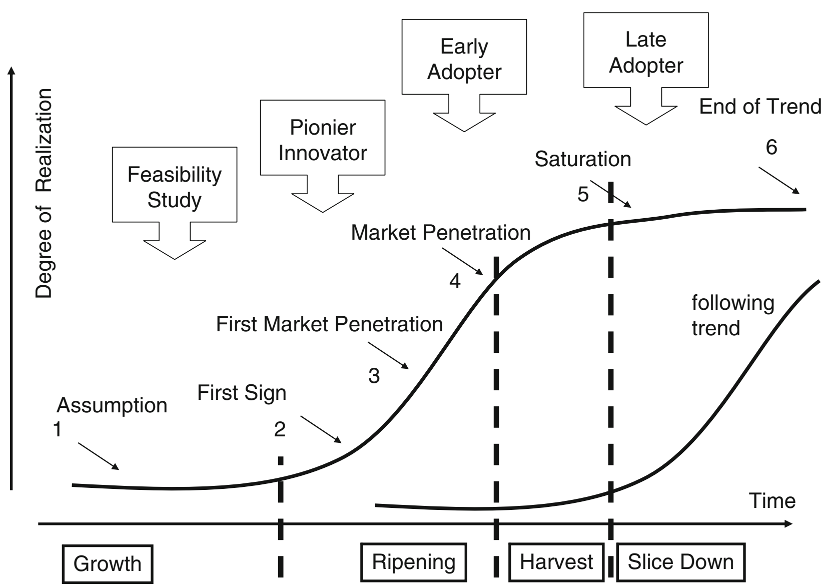
The table is a worksheet of the author in cooperation with enterprises

Table 2 Business participation in the trend "Sensorintegration"

Fields of application	Technical description	Business-approach
Hygrometer	Basic material is only weakly hygroscopic, maybe works by conductivity measuring	Poor technical application know-how, poor market knowledge.
Force sensor	Material must be able to form strong deformations by use of the strain effect. Precision and stability demanded.	Only application competence, if metrologically not very demanding, good market competence.
Temperature sensor	Good interaction, unclear stability and linearity.	Low application competence in this technique. No market competence.
Pressure sensor	Weaker connection, since application medium is not a compression spring.	No application competence in this technique. No market competence.
Distance measuring	Good chances by forming potentiometers	Good application competence, good market competence.

The table is a worksheet of the author in cooperation with enterprises

Fig. 4 Life cycle analysis



2.4 Looking for Industry

The list of all possible business lines is checked step by step with respect to the application portfolio as shown in Table 3. Criterion: are there application cases of the technology which meet the business line. A real hard job starts with this task. As a literature basis e.g. in Germany a trade directory can be chosen from the Internet [13]. Some cases surely are not found because they simply are not listed here. It is advisable that only such applications influence the consideration about which there is a minimum of knowledge. This leads to the fact, that the choice of the participants discussing these facts is extremely important. These can be experts and staff members. The considerations of the numerous business lines with respect to the products are really different. In the liquid level measurement technique the accuracy especially of the zero point is important. This is not the case for toys. Here a sensor every time can be readjusted and in addition, the prize is also extremely low. In addition, there is a decision needed, whether the sensor should act as a switch or as a continuous measuring device. A force sensor for consumer market, e.g. a weight sensor, demands less long term stability because of continuous self calibration.

2.5 Rough Specification of the Product

The technical specification must be newly designed for every scheduled application. An example is indicated in Table 4. It illustrates how the technology is able to meet the requirements of this application. It must also fit the line of business. If a product is extremely accurate and the line of business does not need this at all, it can lead to increased costs. As

Table 3 Characteristics of industry

Industry	Characteristics	Application
Aero-space	High certification level	
Medicine	High accuracy and certification level	Position
Consumer	Price important, not accuracy	Scales weight measurement, blood pressure sensor
Automotive	Price, reliability	Flow measurement touch sensor, safety belt
Military	High price and certification level	

The table is a worksheet of the author in cooperation with enterprises

Table 4 Comparison of specifications

Determing the set/actual comparison values

	Actual	Set	Remark
Accuracy	5% full scale	3% full scale	To be fit
Stability	9% full scale/a	4% full scale/a	To be fit
Hysteresis	1% FS	3% FS	To be improved with the mechanical construction
Prize	5 € (10.000 components)	3 € (10.000 components)	Production problem
Overload	Feasible	Feasible	Mechanical bedstop construction
Sensibility	5% per Full scale and strain unit	5% per Full scale and strain unit	To be fit

The table is a worksheet of the author in cooperation with enterprises

Table 5 Lateral effect

Tendency	Lateral effect	Consequence
Flexible room heating in a house	Remote steering by a mobile phone	
	Opening of windows should be recognised	Sensors for opening of windows
	Movement sensors	Together with burglary devices
	Installation of a computer	Trade PC or self made device
	Lower prizes needed	Raise quantity of units

The table is a worksheet of the author in cooperation with enterprises

a result a verification shows, whether this product runs as scheduled.

2.6 *Looking for Lateral Effects*

Innovations rarely go along the straight way provided for them. They frequently fulfil, their intended purpose besides, a number of properties which were not in the context of the original philosophy.

Examples for this are:

Edison invented the gramophone with the intention to record the conversations and to safeguard them for contractual questions. He celebrated the trump with the adaption of music in the consumption area.

The personal computer, originally established as a typing machine, was driven in his performance by computer games and videos, programmes which need extreme CPU performance and storage capacity.

The counter example is also right: an innovative electronic iron without the well-proven bimetal controller. An innovative renewal with electronics needs a power supply, monitoring system and switches. The benefit is difficult to calculate. The iron gets more exact. The customer, however, does not notice this. Only a replacement of electronics instead of mechanics is not sufficient. The lateral possibilities of the new technology need to be introduced. Additional features have to be employed. Functions like the switching off in case of danger or burning of clothes should be recognized. Engineers who know about the technical application and know how of combination are demanded here.

Table 5 shows an example of the innovation “individual room regulation” in order to save energy. Another point of view with respect to a well heated room is needed. The new innovative thesis is: only in the moment, when a person enters a room, this room is heated. It then will last for some time until this room has reached its final temperature.

3 Conclusion and Outlook

Finally the idea for a product has designed and also can be quantified. All features are written down in a list shown in Table 6.

Table 6 Preliminary product task

Properties	Description
Business line	Remote steering by mobile phone
Function	Detection of opened or closed windows
Additional function	Burglary device integration
Ccompetition	Stand alone systems
Unique selling proposition	Availability
Production Cost	120 €
R+D cost	120.000 €
....	.....

The table is a worksheet of the author in cooperation with enterprises

Now it is clear what kind of applications can be afforded with the new technology. Target markets can be defined, advertising, distribution channels. New within this methodology is the strict sequence with which this problem is worked off. There a language is used which is also accessible to engineers. This working paper can be picked up later again and again and updated at every time. This corresponds to the execution of a creative process. It represents a knowledge-safe for the enterprise. It also makes sure, that no product concept is established for which the relation to future trends is not contained.

This methodology was tested with several individual examples among medium sized enterprises for mechanical and electrical engineering. In the completion it can be realized with the software excel or word. But a computer program alone wouldn't solve the problem. It is crucial, that a master version is laid down in a server in which also variations are documented. This is an ideal case for a WIKI, to establish a self developing documentation. In this way there is documentation generated about the systematic behaviour of innovation.

In a next step this methodology will be widened in the scope to bigger companies and also include the organisational context. Other business lines like service industries, trade and commerce should also be included. It seems promising that the methodology also works satisfactorily in these cases.

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Knowledge Management Approaches for Creative and Inventive Design in Global Product Development

Knowledge Management for Mass Customization

J. Daaboul, A. Bernard, and F. Laroche

Abstract Nowadays is the era of mass customization which satisfies the more demanding customers who seek uniqueness. Nevertheless it is not that evident to put in place such a strategy, many difficulties have to be handled at first. Products should be designed for mass customization, and then they should be manufactured and delivered specifically for a specific customer. Therefore an efficient information sharing and knowledge management are crucial for MC, for the main issue of MC is to correctly communicate customer desires. This article discusses how KM is an enabler for MC in the light of a European project DOROTHY.

Keywords Mass customization · Knowledge management · Product design

1 Introduction

Due to the more demanding customers, the internet revolution, shortening of product life cycles, increased competition, the integration between the different parts of a supply chain [1, 2], and the internationalization and digitalization of markets [3], mass customization (MC) has become lately an important strategy. MC was first identified by Davis in 1987 [4] as the ability to produce personally designed products. Customers nowadays prefer quality, style, and uniqueness over homogeneous products [5]. And many companies have successfully applied this concept and offered customized products to their customers, such as National Bicycles Industrial Company of Japan, Hewlett-Packard, Motorola, General Motors, Ford Motor, Benetton, Chryslers, and Dell. But, even though it is an attractive strategy, its implementation remains a difficult task. Da Silveira et al. [2] declare that the methods to implement MC are agile manufacturing, supply chain management, customer-driven design and manufacture, and lean manufacturing. The core of MC is to design a product that can be customized by every customer and produced with a cost similar to that of mass production. A product is no more designed for MP but for MC. Trying to implement customization without a much rationalized product line and a family architecture/platform of products might be risky for the manufacturing firm. This will lead to design proliferation and will turn the system chaotic. "Customization cannot be successful unless, products are designed for customization" [6]. Moreover, the information gathered directly from customers should be used to improve the products'design. In MC and differently to MP we don't anticipate or forecast customers' desires, We know them directly from the customers themselves. And this valuable information should be correctly captured, stored and reused while designing products. This article presents a mapping between MC process and knowledge. It is organized as follows: in Sect. 2 we present the related works, in Sect. 3 we discuss the particularities of KM when applied for MC. Finally we conclude in Sect. 4.

2 Related Works

2.1 Mass Customization

The literature presents many definitions for mass customization; it was first identified by Davis in 1987 [4] as the ability to produce personally designed products and services at a cost similar to that of mass production. Then it was defined by Pine [7] as the capability to provide individually design products and services to every customer throughout high process agility, flexibility, and integration. Hart [8] seemed to combine the two previous definitions into one. Hart also viewed mass customization as a performance ideal allowing customers to have the product they want, as they want it, any time they want it, and anywhere they want it. Furthermore

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Yang and Li [9] viewed mass customization as a" kind of production mode for customized products supplied to the individual customer in random quantity, or to multi-variant small batch markets, based on mass production with high efficiency, via the re-combination of product structures and manufacturing process, using a series of modern information technology, advanced manufacture technology and modern management technology with the cost and speed of mass production". Also lately, Huang et al. [10] identified mass customization as a performance competence.

Mass Customization process: A MC process is formed of several subprocesses and includes the following steps:

At first is customer is identified by saving data about his name, contacts, address... Then depending on the product and on the type of implemented MC, some measurements are taken. Next the customer personalizes his/her product with the help of a salesman or directly via the product configurator. This step can be achieved online once the customer has an ID. Following the placement of order is achieved. Then the order is processed. Two cases appear, the first being when the personalization takes place in the shop. In this case, the order processing is done in the shop, and then the salesman prepares the order by achieving the final product assembly or by adding additional goods or services to the product. Finally he delivers it to the customer. In the second case, personalization doesn't take place in the shop, but in the factory either at the fabrication level or at the assembly level. In this case, the orders are sent to the factory that processes them, and then plans for their production (setting routes, allocating resources, scheduling machines...). Next, purchasing of needed material or semi-finished products is done. Following the specific products of the order are fabricated, and then assembled to be finally delivered to the customer's preferred delivery address. All these are shown in Fig. 1.

Before starting the customization process, a catalogue of customization options is developed and provided by the company which already have developed and designed shoes for MC, and have made all the necessary changes in its value chain to cope with such a strategy.

The MC process is customer centric, meaning that it starts by a customer order and ends by delivering the customized order to the customer. All the subprocesses should be customer centric as well. Eventually the aim of MC is to produce exactly what a specific customer wants and with a cost close to that of MP.

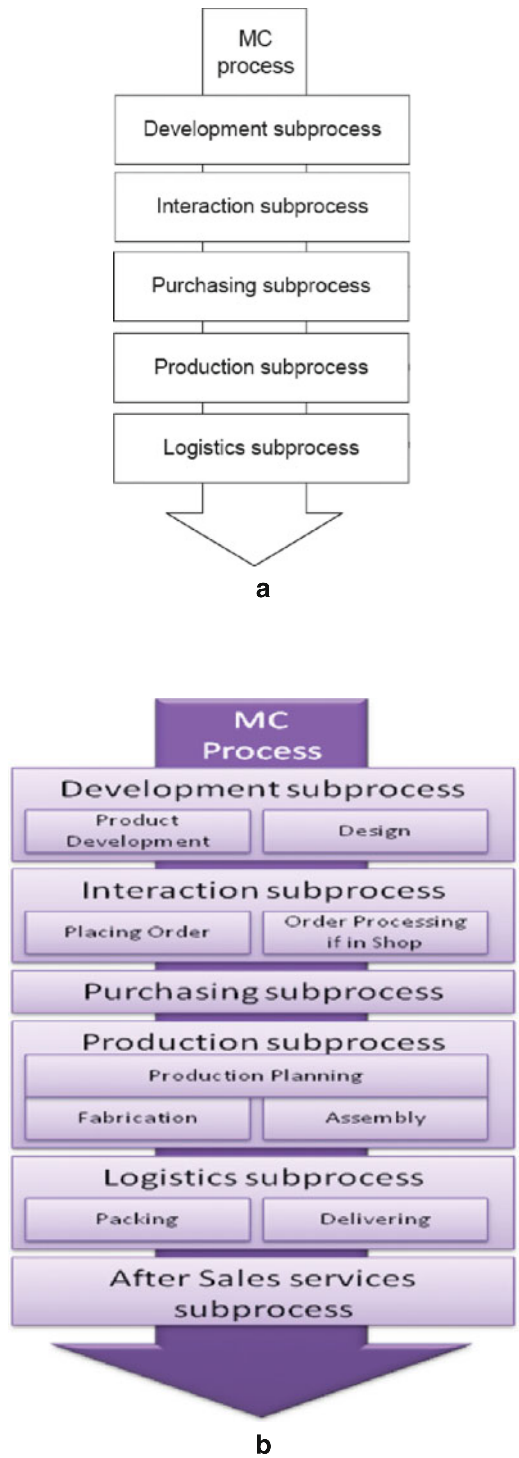

Fig. 1 (**a**) MC process from Blecker et al. [11]. (**b**) Updated MC process

2.2 Knowledge Management

Knowledge management can be seen as a business process that identifies, collects, creates, organizes, stores, and distributes valuable knowledge in order to apply it to problems and use it to attain certain goals [12].

It leads to the improvement of customer relationship management, supply chain management, and product development [13]. Knowledge management is necessary to a company for achieving innovation in products, processes, services, and organization. Also, it leads to reduction in costs of design, production, distribution, and others [14]. The literature presents many definitions for KM. From these definitions four main principles to be considered when managing knowledge are highlighted. These are that knowledge is connected and is applicable in new environments. That KM is an action or a catalyst, and its solutions depend on having a knowledge sharing culture [14]. Many aspects need to be considered when managing knowledge. First of all, Knowledge is used by different users at different times, and is transferred from a user to another knowing that not all users are considered by the same point of views. Secondly, the used software influences the modeling task since it offers certain views leading to information redundancy. Finally, the transformation of knowledge needs to be modeled too, because knowledge is not static [15].

2.3 DOROTHY

DOROTHY which is a medium size research project aiming at enhancing the competitiveness of the European shoe industry, by developing the necessary tools and methods to support a customer driven design and a multi-nation multi-site factory.

DOROTHY' mission is to offer the possibility for a customer anywhere in the world to co-design his/her shoes that will be manufactured in a multi-site multi-nation factory and delivered to him/her. In order to achieve this mission, DOROTHY tackles three main scientific and technological objectives:

- Cluster 1: Design tools for customer driven and customer fit shoe
- Cluster 2: Design tools for advanced industrial engineering of multi-site and multi-nation production systems and factories, based on the customer driven shoe
- Cluster 3: New business models for the multi-nation multi-site shoes

3 Knowledge Management for Mass Customization

Knowledge management (KM) is a main factor and tool for the success of a MC system [16]. It is a critical factor for successful new product development and design; it is not an advantage but a necessity. These two activities cannot be achieved efficiently and effectively if the product developers have access only to explicit knowledge. They should also have access to tacit knowledge gained from the experts and workers on the production processes. This might be achieved by job rotation, allowing them to experience the production steps and get a deeper insight on what is feasible, and optimal as a design. The biggest advantage of mass customization is the knowledge gained directly from customers, and then shared with the product development department.

Differently to mass production, in MC case, knowledge about what the customers prefer and their reaction to existing designs can be directly gained, not through the marketing department. This knowledge should be well stored and managed to be efficiently used for better product development constituting the update flow which is the use of customer collected data for design of new and innovative products and for improving the marketing strategy, product platforms, design configurator and production processes [17]. But what knowledge and information is needed for what activity and to be used for what is the main question. Table 1 maps the different activities of the MC process with their needed information and knowledge. As shown in this table, for most activities knowledge about both the product and its production processes are needed. Therefore for a successful MC process the two data models of product and process should be linked. Figure 2 shows the product data model for DOROTHY.

When the customer personalizes his/her shoe, his/her choices are reflected in the shoe components, thus from customer requirements we deduce the correct shoe components, and from customer feet sizes we deduce the correct last size. Having all the information needed about the customer and his/her customized shoe; this information should be used to deduce the related production process routing. This can be achieved via a product configurator that links the two data models together, as shown in Fig. 3.

Moreover, customer preferences should be used to enrich the product knowledge to conceive and design better shoes that more satisfy customers' needs. This is also shown in Fig. 3 [18].

4 Discussion and Conclusion

This chapter discussed knowledge management for mass customization in order to better conceive and design products. We showed that a link between knowledge of the product and that of the process should be established, especially to automatically generate from customer choices the product characteristics and the related process routing and artifacts. Moreover, information about customer preferences should be used to increase the product knowledge to develop

Table 1 Information and knowledge needed for MC process activities

Activity	Needed information	Needed knowledge
(SALES) placing order (customizing product)	• Customization options • Design constraints • Price of product • Delay time (for order processing) • Conditions of cost variability	• Salesman knowledge about the product and its production • Customer knowledge about the product • Knowledge about customer preferences and previous designs
Order processing	• Orders (product characteristics and quantities)	• Knowledge about the product • Knowledge about production processes
Product development	• Production constraints/feasibility • Evaluation of previously developed products • Market evaluation of the generated ideas • Acceptable price for customers • Market trends • Competitors similar products	• Knowledge about customer's preferences • Knowledge about production processes • The tacit knowledge gained at the critical production processes • Knowledge about product
Design	• Generated and accepted ideas from product development team • Customer's evaluation of the generated ideas • Production feasibility (from production dept) • Customization strategy	• Knowledge about customer's preferences • Knowledge about production processes and production capabilities (implementing collaborative engineering/design)
Production planning	• BOMS • Orders (product characteristics & quantities) • Resources capacity/usage • Delivery due date • Inventory	• Knowledge about product • Knowledge about product processing • Knowledge from previous similar cases
Purchasing	• Orders (product characteristics and quantities) • Inventory • Suppliers flexibility • Supply strategy • Forecasted demand • Replenishment lead-time	• Knowledge of quality of supplied material • Knowledge from orders (most requested product. . .)
Manufacturing	• Orders • Routings/schedules • BOMs • Delivery deadlines	• Knowledge about product • Knowledge about production processes • Experience/knowledge gained from previous similar cases
Assembly	• Orders • BOMS • Schedules • Delivery deadline	• Knowledge about product • Knowledge about production processes • Experience/knowledge gained from previous similar cases
Delivering	• Orders • Customers	
After sales services	• Customers evaluations • Incorrect orders	• Knowledge about product • Knowledge about production processes

and design sustainable products, and in DOROTHY case sustainable shoe designs. As future works, Knowledge as a support for decision making will be studied. Thus questions such as where and how knowledge is needed all along the MC process for making a decision will be studied. Moreover, the methods of conception should be evaluated to be able to offer products the most user-centric. This evolution is a progressive process due to the increased complexity of such products due to their high diversity and shorter life cycles.

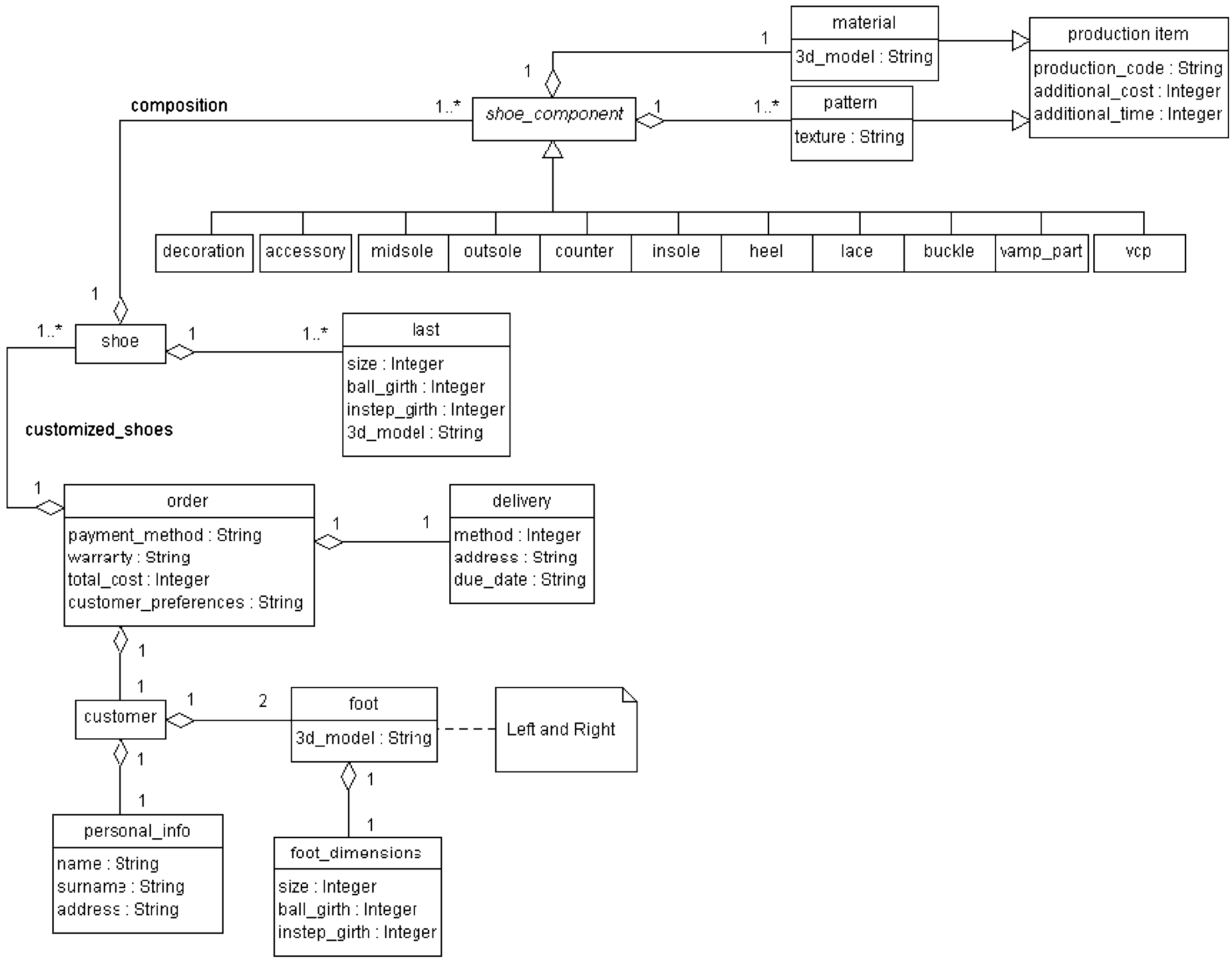

Fig. 2 Product data model for DOROTHY [19]

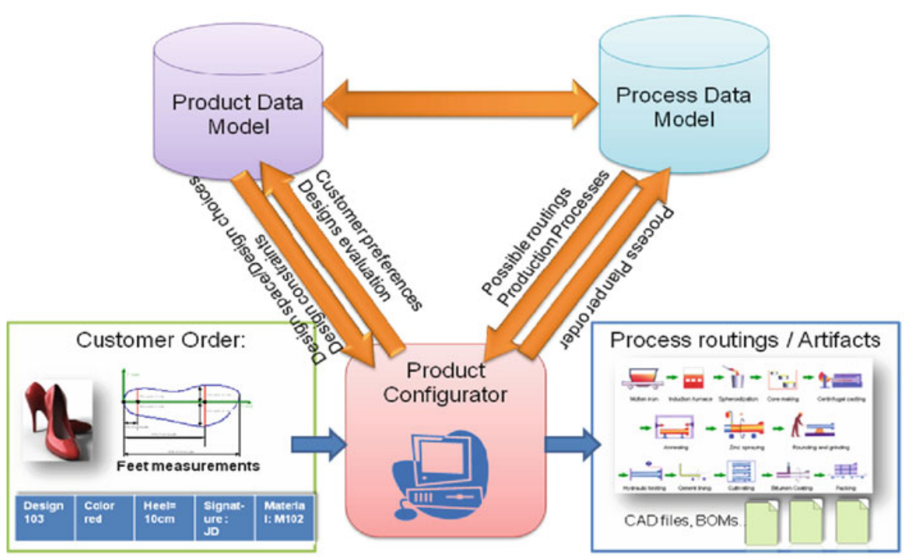

Fig. 3 Product configurator

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Using Ontology for Design Information and Knowledge Management: A Critical Review

Y. Liu and S.C.J. Lim

Abstract Ontology has been identified as a feasible modeling solution for rich design information and knowledge representation. From previous studies, the applications of ontology in design engineering have shown promising progress. This chapter provides a critical review of the recent achievements in utilizing ontology for design information and knowledge management. The applications of ontology in the three major categories are explicitly discussed. Most importantly, a number of research issues concerning the application of ontology in design engineering have been identified and suggested. Finally, based on the current state of research, a few promising future research directions are also briefly discussed.

Keywords Ontology · Design information · Knowledge management

1 Introduction

In today's design engineering scenario, both design and manufacturing companies are constantly investigating ways to offer better products in different aspects such as cost and product performance in order to meet with different customer expectations. The ever changing customer tastes on product requirements have forced design and manufacturing companies to offer more product choices that target at different market segments. Taking the amount of design information generated during the design process into consideration, the management of design information and knowledge has become a critical issue worth investigating. Design information refers to information generated during the design of an artifact, such as artifact associated design specifications, functions, materials and manufacturing process. This information are usually recorded in design documents, that may include design proposals, final design drawings and engineers' logbook, handbooks, patent documents, online catalogs or magazines. With the advent of computerized design tools and database system, the challenge lies in processing these large amounts of information in order to effectively and efficiently capture, index, store and retrieve them, as well as to discover meaningful knowledge for timely decision making.

For the majority of design and manufacturing organizations, design information and knowledge are regarded as an important asset for the production and delivery of their products or services, where it also plays an important role in maintaining the sustainability of organizations [1]. Advances in information communication and technology (ICT) and the realization of more affordable and powerful computers have revolutionized how design information is being created, indexed, stored and retrieved. From a previous study, it is discovered that design engineers often sought solutions from past design cases in solving their design problems where they spent 20% to 30% of their time retrieving and communicating design information [2]. Besides the issues involved in performing search and retrieval operations, a design representation that enables designers to look at design knowledge at different perspectives, either in new or unfamiliar design situations is equally important [1]. Ahmed and Wallace [3] found that in their studies involving 633 queries, novice engineers were only aware of what they needed to know in only 35% of all queries compared to experienced designers. Their findings suggest that a design representation that supports both experienced and novice designers in identifying key information during the design query process is crucial. In another study, it is revealed that a typical manufacturing organizations can have 7–12 information systems (IS) that are tailored for different needs [4]. However, these IS usually differ in terms of technologies, standards and underlying information architecture, causing expensive operations on information exchange and integration at later stages of

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design [4]. Consequently, a unified information model that allows interoperability of design information across different IS for efficient search, navigation and retrieval is essential towards streamlining the design process.

With respect to all these requirements, ontology is identified as a feasible information modeling approach that possesses rich knowledge representation capabilities for comprehensive design information and knowledge management. Ontologies are the basic building blocks of Semantic Web where it allows the mapping of information across different perspectives. Different from a taxonomic structure that describes information in a concept hierarchy manner, ontology is able to describe relationships by defining multiple semantic relationships between concepts and entities of the ontology, as well as to other ontologies. This ability allows different context of design information to be semantically modeled and new design knowledge at different perspectives to be suggested.

In the context of design engineering, there are already a substantial number of works reported that have illustrated the use of ontology in different areas of design engineering. Harnessing the semantics of ontology, the practical applications of ontology in design engineering have presented great potential in solving some of the issues of design information and knowledge management, such as better design information storage, search and retrieval; semantic interoperability for federation of design information; and intelligent product configuration. PricewaterhouseCoopers, one of the world's largest professional services firms, have recently mentioned the importance of business information context and semantics for better decision making, where they have predicted that "a transformation of enterprise data management function driven by explicit engagement with data semantics" will take place in the next 3–5 years [5]. In relation to this, we also believe that similar efforts of adding the semantic dimension in design information modeling using ontology will likely to occur given the rising interest of the design communities towards the use of ontology in recent years. Therefore, a critical review that covers the state of the art issues in development and application of ontology in design engineering is needed in order to identify possible future research directions.

This study attempts to provide a critical review on the use of ontology for design information and knowledge management. The rest of this chapter is organized as follows. In Sect. 2, we present the reviews on studies related to ontology development in design engineering. Several key applications of ontology in design engineering are comprehensively covered in Sect. 3. Section 4 discusses about the research issues surrounding various aspects of ontology applications in design engineering and some potential future applications. Section 5 concludes.

2 Ontology Modeling and Development in Design Engineering

Ontology consists of a set of concepts, axioms, and relationships that describe a domain of interest, and can be regarded as an explicit specification of a shared conceptualization, that can be taxonomically or axiomatically based [6]. In the engineering perspective, examples of concepts are "fastener" (device and structural oriented concept), "rotate" (functional oriented concept) and "plastic" (material oriented concept), that exemplifies the underlying semantics behind a domain. The concepts and relations in ontology need to be explicitly defined before its deployment in design engineering. In the area of library science or computer science, the efforts in creating ontology have started in the mid-1980s, where we witness the creation of Cyc ontology and WordNet. Cyc ontology attempts to model a comprehensive ontology of everyday common sense, and WordNet serves as a comprehensive lexical ontology for natural language processing (NLP). Later on, there are other ontologies that are built for different purposes, such as GENSIM (for genetic simulations), PLINIUS (for mechanical properties of ceramic materials) or Unified Medical Language System (UMLS) (for modeling medical concepts). A comprehensive survey and review on the design of all these ontologies are covered by Noy and Hafner [7].

In terms of ontology development, there are several early studies on the methodology for ontology development that are being proposed in the area of library science and computer science. The work by Gruber [6] is perhaps one of the earliest studies that has presented design principles for ontology development meant for knowledge sharing. Later, three most representative methodologies for building an ontology being presented: (1) Gruninger and Fox [8] proposed a methodology of designing and evaluating an ontology, that is used in developing the TOVE (Toronto Virtual Enterprise) project ontology; (2) Uschold and King [9] proposed a methodology for building enterprise ontology for enterprise modeling processes; (3) Fernandez et al. [10] presented a more systematic approach for building ontology from scratch, called METHONTOLOGY that is applied in building a chemical ontology. The review of these three methodologies can be found in Pinto and Martins' review [11]. Another notable study that serves as a useful guide in building an ontology is proposed by Noy and McGuinness [12]. Their approach to ontology engineering, named Ontology Development 101, presented a knowledge engineering approach in creating ontologies. All these studies have presented useful practical guidelines in ontology building that are adopted by researchers in the design engineering domain.

There are also other methodologies for ontology building that are specifically tailored for the design engineering domain. Ahmed et al. [13] have attempted to develop a methodology for ontology development that aimed for indexing design knowledge. Their methodology focuses on the user's domain, where they have identified four root concepts: design process, function, issue and product in their engineering design integrated taxonomy (EDIT). However, their methodology does not explicitly study the complex inter-relations among the root concepts. Another methodology of building an ontology is proposed by Sarder et al. [14]. They have introduced a methodology called Domain Knowledge Acquisition Process (DKAP) for creating ontology of product and process design. Utilizing the knowledge engineering approach, DKAP presented a systematic approach in obtaining domain specific knowledge by using an ontology description form that is based on IDEF5 standard. Nanda et al. [15] applied the formal concept analysis in their methodology to develop domain specific ontology for a product family. The formal concept analysis approach is used to identify similarities among a finite set of design artifacts based on their properties and to ensure consistency in obtaining domain concept hierarchy.

From the previous literature, some of the early related works of ontology application in design engineering domain are meant for the purpose of systematizing specific domain knowledge, that includes defining and developing ontology for product configuration [16], ontology for engineering design activities [17], port ontology [18] and ontology of functional knowledge [19]. These ontologies are mostly developed based on extensive domain literature studies that aimed for representing domain specific knowledge at a higher level of abstraction for knowledge generalization. There are also some other research efforts that have modeled and evaluated ontology using empirical approaches (e.g. survey & interviews), such as the EDIT discussed earlier. The ontology developed in this way presented a more specialized area of knowledge for specific purpose, based on user needs for example that are also important towards certain domain of interest.

3 Ontology Applications in Design Engineering

This section describes some of the existing works on ontology applications in design information and knowledge management. Figure 1 illustrates an overview of ontology application in design engineering. We categorized the applications of ontology in design engineering into three major categories: (1) design information annotation, sharing and retrieval; (2) interoperability; (3) product design configuration. The detailed descriptions on each of the applications are described in the following sections.

3.1 Design Information Annotation, Sharing and Retrieval

One of the most widely preferable uses of ontology in design engineering is for the annotation, sharing and retrieval of design information. We view this area of application in two perspectives: one is where ontology functions as the underlying knowledge base to aid designers in annotation task for better retrieval, and the other one is where the ontology itself is the underlying knowledge schema for intelligent retrieval by designers and engineers. In the first perspective, ontology is used as the pre-determined and pre-defined knowledge that assists designers in annotating design information. For instance, Kitamura et al. [20] have introduced a schema named "Funnotation" for functional annotation purpose based on their functional ontology. While their annotation are accomplished using manual annotation tools, Li et al. [21] used a pre-defined engineering ontology to semi-automatically create semantic metadata of textual engineering documents. Another study by Catalano et al. [22] used a car aesthetic ontology to semi-automatically annotate two and three dimensional car models using image processing techniques. Ontology-based annotation ensures a more efficient indexing and retrieval of design information where ontology can function as the semantic indexing structure for semantic-based search and retrieval.

In the second perspective, ontology functions as knowledge base for storage of design information. Harnessing the semantic capabilities of ontology, ontology can model complex inter-relations between information, and provide users with a powerful knowledge base to complete various decision support tasks. For example, ontology can be used as functional knowledge base for functional knowledge retrieval by designers in different viewpoint [19]. In the field of engineering analysis, Groose et al. [23] used an ontology-based knowledge base named ON-TEAM to effectively share information on engineering analysis model among engineering organizations. Witherell et al. [24] studied an ontology for optimization (ONTOP) as knowledge base that can assist engineers in selecting the best engineering optimization models. Function as knowledge bases, these studies have also proposed knowledge acquisition interfaces to further populate the ontology to enable design knowledge management where additional new design cases can be effectively stored and retrieved. Lim et al. [25] have presented an information management and retrieval framework in product family design using a semantically annotated multi-facet product family ontology. By using a case study, they have demonstrated the benefits of faceted search in performing

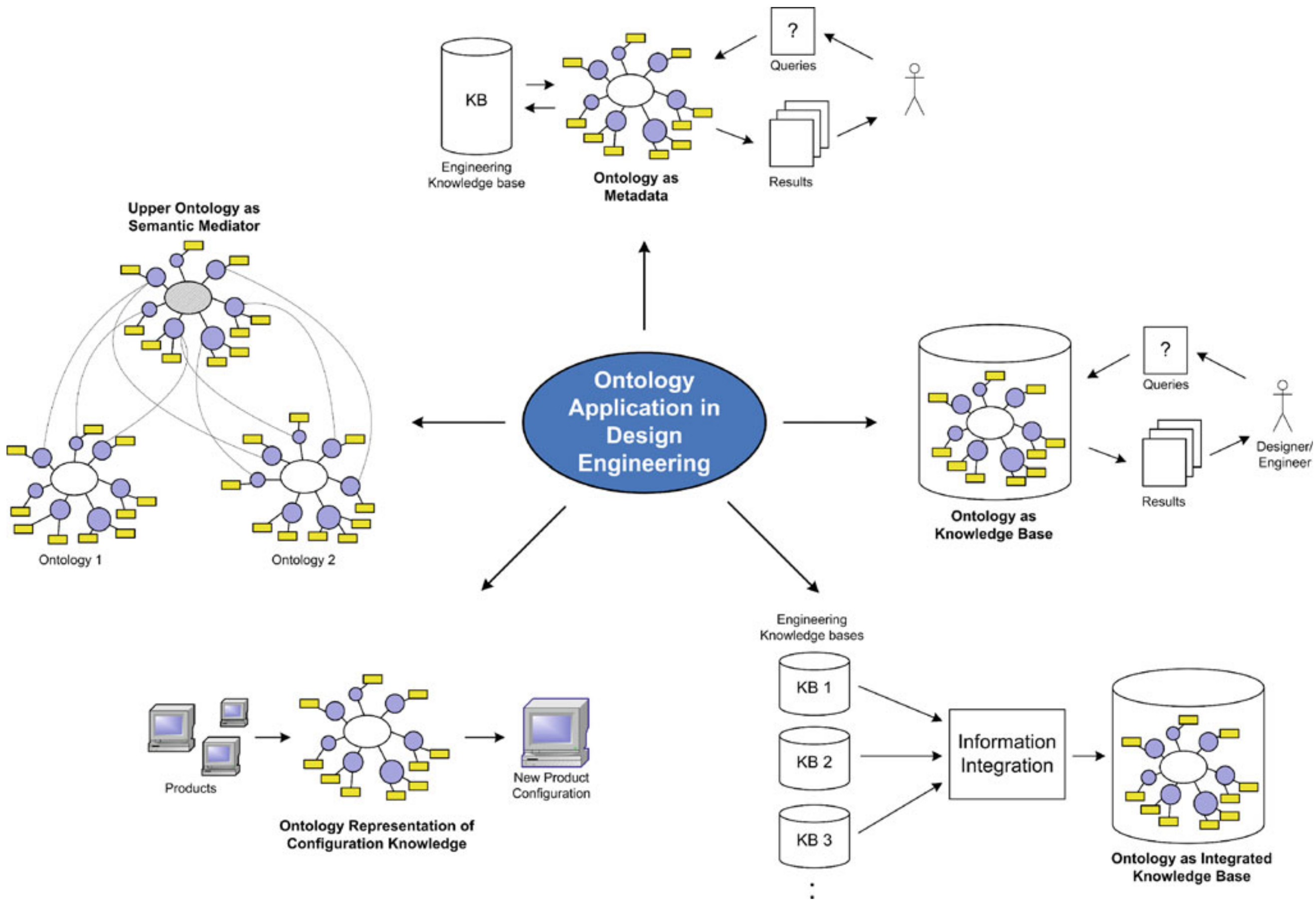

Fig. 1 Overview of ontology application in design engineering

tasks such as intelligent variants configuration and product platform search.

3.2 Interoperability

The formal conceptualization of domain knowledge embedded in ontology makes ontology useful to enable interoperability among heterogeneous knowledge base or engineering applications. Ontology in such a case is often used as a common mapping structure to achieve common understanding among different ontologies. In this context, the ontology is also commonly known with the "upper ontology" concept, where semantic ambiguities are resolved by providing common terms or vocabularies at a higher level of abstraction. An example on this topic is to apply ontology for solving the interoperability between a computer-aided design (CAD) application and computer-aided process planning (CAPP) application using feature ontology [26]. Ontology serves as a mapping mechanism to allow interchange of information across two different systems. Oh et al. [27] presented a method to enable semantic mapping of different business documents by utilizing ontology as the semantic gateway. Lin et al. [28] proposed the use of manufacturing system engineering (MSE) ontology to facilitate the semantic interoperability across extended project teams. Another study by Cho et al. [29] adopted a meta-ontology in part libraries integration where it is used for unified search among distinct part libraries. It is noted that most of these mappings between ontologies are achieved manually via specific tools.

Another stream of research in this area witnesses the use of ontology as the knowledge structure for integration of information or knowledge base. In this context, ontology can be used to integrate information sources into a unified ontological representation for information sharing. For instance, Bellatreche et al. [30] used an ontology to automatically integrate electronic catalogues to ensure consistency in data semantics. A recent study by Zhao and Liu [31] have also discussed an ontology-based methodology for encoding EXPRESS-driven product information model to web ontology language (OWL) and Semantic Web rules language (SWRL). Ye et al. [32] used a supply chain ontology (SCO) as the underlying structure for implementing semantic integration of information in supply chain applications. These studies aim to use ontology as a unified information model, and to convert design information in older ontological formats such as RDF into newer ontological representations in OWL. A good review on interoperability and information integration are discussed in a review by Ciocoiu et al. [33].

3.3 Product Design Configuration

Another important research area in design engineering where ontology is applied is product design configuration. Product configuration can be a complex process as it involves multiple aspects such as rules and constraint satisfaction. Ontology is able to model the relationships among different design artifacts of a product and offers an approach to comprehensively model the attributes, constraints and underlying design related rules for intelligent product configuration. With respect to this, an early study by Soininen et al. [16] have presented a general ontology of configuration, where detailed conceptualization of knowledge on product structures are explicitly defined. McGuiness and Wright [34] presented a conceptual modeling for configuration using description logic-based approach that focuses on the assembly process. Felfernig et al. [35] presented a configuration knowledge representations for semantic web applications using ontology languages. Most of the early works reported so far present a conceptual description on how a product configuration problem should be represented using ontology. A recent study by Yang et al. [36] have explored the use of ontology for rule-based product configuration. Different from single product configuration, ontology is also being proposed as a feasible modeling scheme to represent a product family. Nanda et al. [15] have represented a family of products using a product family ontology as a unified information structure for a product family. Lim et al. [37] have also proposed a new approach towards product analysis and variants derivation based on a semantically annotated product family ontology. Their study have shown the merits of using ontology in supporting designers for product family redesign purpose.

4 Future Research Issues and Applications

From the previous discussions on the applications of ontology, it is clear that ontology can play different roles and can be applied in design engineering in multiple ways. In such a case, explicitly defined ontologies are necessary to ensure successful deployments. However, developing ontology is a challenging task if we consider the time and efforts required. We note that majority of the ontologies are defined manually based on intensive domain literature studies, where human annotators are employed to annotate domain specific concepts and relations based on their comprehension of domain knowledge. While such an approach is essential in deriving non-trivial semantic relations and rules, the process will eventually become a burden for human annotators as the ontology evolves with incremental information. In view of the large amount of product offerings available in the market, effective means of semantic annotation for ontology development that require less human efforts is highly desirable. In this sense, the approach should be able to assist human annotators in ontology definition by providing useful suggestions for annotation. The recent trends in the field of ontology learning, with tools such as Text-to-Onto [38], and OntoLearn [39] to extract domain ontologies from corpus, can shed light on the issue of ontology development.

In relation, it has come to our attention that most of the studies do not emphasize on further updates and population of ontology. Despite the fact that a higher level ontology (e.g. upper ontology) that contains generic knowledge representation may not require much changes, other specific ontologies such as product specific component or functional ontology, user requirements ontology or marketing strategy ontology are subject to change when design information changes. This implies that the knowledge, that is once relevant, may become obsolete and new information may be discovered after the ontology has been explicitly updated. Another problem is on the annotation changes that are caused by ontological changes. The annotation on resource such as design documents or other related ontologies may no longer be valid. The dynamic updates on these annotations are also a challenging issue. To the best of our knowledge, we observe that there are still very few studies that address all these important issues. We believe that all these are important in the design engineering perspective as changes in design information will normally trigger the “chain effects” in design. For instance, the changes in upstream design activities (product specification changes) can dramatically affect the downstream design activities (manufacturing plans, packaging, supply chain, etc.). Therefore, it is desirable to study the evolution of ontological structures due to design information changes, and its impact towards the whole design process.

Another issue worth investigating is on the ontology mapping for interoperability. The mapping among ontologies is important in the aspect of integrating knowledge bases for knowledge discovery. However, the process of mapping ontologies is a challenging task. Most of the previous studies adopted a manual approach in generating the mapping between ontologies of which, in our opinion, is time consuming and tedious. For scalability, we reckon that this is an important issue as the incorporation of different aspects of ontologies, like function and manufacturing process, can be performed in a more automated fashion to enable better comparison of products. This challenge is also fundamental towards the realization of Semantic Web paradigm in the design engineering domain. We suggest the use of intelligent approaches to assess semantic relatedness between concepts, entities and properties of different ontology for semi-automated or automated mapping of ontology. A review of tools proposed for this purpose, such as GLUE, ONION and FCA-Merge, are researched in a study by Choi et al. [40].

In the ontology engineering perspective, ontology evaluation and validation is another important issue where much attention should be given. The ontology developed need to be evaluated and validated to ensure the consistency of ontology. We find that this part of research are often neglected and rarely reported in previous studies. Ensuring the validity of ontology is a complicated task that usually involves domain experts and explicit human judgments. In order to reduce human efforts and ensuring better evaluation and validation, building ontology collaboratively is one of the ways to define better upper ontology where ontologist can have a shared consensus during the process of ontology development. Web-based ontology editing tools, such as Web Protégé,[1] can be a promising starting point towards collaborative ontology evaluation and validation.

Based on the capabilities and the current trends of using ontology in design engineering, we are able to foresee a few other potential applications that are worth of investigation. Some of the potential future works include, but are not limited to, the annotations of non-textual design information such as sketches, CAD models and design animations; the representation of sequential design information such as event logs for design changes, and the cognitive aspects of design, such as design rationale, aesthetics and styling of design artifacts. All these research areas are interesting topics that await further investigation.

5 Conclusion

Ontology is identified as a feasible modeling solution for rich knowledge modeling scenarios towards comprehensive design information and knowledge management. The practical applications of ontology in design engineering have presented a great promise in the design information and knowledge management perspective. This study provides a survey on the state of the art application of ontology in design information and knowledge management. We have discussed about the methodology for ontology development that includes established guidelines proposed in library science and computer science as well as those proposed in the design information domain. We have also identified three major categories of ontology applications in design information and knowledge management: (1) design information annotation, sharing and retrieval; (2) interoperability; (3) product design configuration. The applications of ontology in the three major categories are presented. Furthermore, a number of future research issues and applications on utilizing ontology in design engineering have been critically reviewed and presented in this chapter.

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A Framework to Support Semantic Interoperability in Product Design and Manufacture

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Abstract Problems related to knowledge sharing in product design and manufacture, for supporting automated decision-making procedures, are associated with the inability to communicate the full meaning of concepts and their intent within and across system boundaries. This chapter proposes a Semantic Manufacturing Interoperability Framework (SMIF) to support interoperable design and manufacture knowledge at the semantic level. The framework uses a heavyweight ontological underpinning and provides a logic-based approach for the reconciliation of domain semantics. The framework has been implemented and the important findings have been documented in this chapter.

Keywords Design and manufacture · Knowledge representation · Knowledge sharing · Ontologies · Common logic

1 Introduction

The ability for manufacturing supply chains to acquire interoperable manufacturing knowledge has become a competitive edge in the global market. The management and traceability of valuable knowledge are considered a significant asset which is directly linked to the production of better, faster and cheaper products, while ensuring increased quality levels. Although heavy investments are being sought for enhancing the management of product and manufacturing knowledge for collaborative product development, yet, the seamless exchange of the knowledge (i.e. interoperability) amongst stakeholders is still not completely achievable.

A number of issues exist which prevent manufacturing companies to tap the benefits of full product development knowledge interoperability. These issues involve, for example, the presence of incompatible data and information structures, different software development approaches and incompatibilities between the semantics of system terms [1, 2]. It is to be pointed out that the development of standards as a resort to resolving interoperability issues is helpful as long as stakeholders are willing to use them. However, even in the case of standards, it has been clearly mentioned that semantic inconsistencies could still prevail as a result of concepts which are not rigorously defined [3].

The type of interoperability problem targeted in the context of this work is related to formal semantics, i.e. the investigation of the definition, interpretation and the meaning of concepts at computational level. In collaborative product development, mismatches occur as a result of (1) the existence of multiple overlapping terms and definitions, dispersed across several stages of the product lifecycle and (2) alternative representations of similar concepts. This inevitably leads to the creation of models aligned with particular views of the world thereby resulting in biases and subjective features [4]. In the event of having to interoperate between heterogeneous models, the task of sharing knowledge is most likely to be challenging due to these cross-domain semantic discrepancies.

In order to contribute to overcoming this problem, the Semantic Manufacturing Interoperability Framework (SMIF) has been proposed and explored, with its core facets highlighted in this chapter. The framework consists of four layers which altogether enable (1) the explicit representation of feature-based concepts in product design and manufacture and their specialisation by different domains and (2) the ability to reconcile cross-domain semantics for knowledge sharing.

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2 Semantic Requirements

It has been firmly recognised that the establishment of interoperability needs to be fostered by the supply of information through both inter-system and intra-system communication [5]. Based on this view and on a perspective related to information organisation, a number of requirements to help support semantic interoperability in product design and manufacture have been investigated. These are briefly identified next, together with an understanding of how the requirements occur.

Requirement 1. Product lifecycle knowledge resides in multiple different but overlapping viewpoints. Activities such as Design for Function, Design for Assembly, Design for Manufacture and Process Planning dictate the nature of the meaning and intent of concepts defined within specific viewpoints. This diversity of perspectives remains a key issue as far as ensuring semantic integrity across viewpoints is concerned. It has been acknowledged that multi-perspective considerations are essential for sharing information [6–8]. Hence, it becomes evident that a progression towards the seamless exchange of design and manufacturing knowledge requires capturing the semantics of concepts from multiple product lifecycle viewpoints.

Requirement 2. In product design and manufacture, key information elements capture the interactions between the semantics of different viewpoints. For example, nominal sizes and dimensional tolerances of features provide important semantic relationships between the Geometric Dimensioning and Tolerancing (GD&T) and machining process viewpoints. Knowing the behaviour of these relationships is vital to drive Design for Manufacture decision support. For this reason, there exists a need for providing semantic relationships between different but overlapping product viewpoints in order to support integrated semantic capabilities.

Requirement 3. Ontologies provide an approach to address interoperability issues brought about by semantic obstacles by fostering a basis for sharing meaning [3]. However, multiple domain ontologies that need to interoperate at the semantic level do not readily do so, as a consequence of their widespread distribution and the overlaps in their content [9]. Continuing diversity of domain ontologies is partly related to the inappropriateness of enforcing an all-embracing common ontology as a basis over which to build up information exchanges [4].

The concept of foundation ontologies has been proposed [10–12] in order to provide a core set of semantics applicable across several domains. However, it has been pointed out that there is an ongoing task of understanding how effective foundation ontology approaches can be tailored to address the communication requirements in manufacturing [3]. This indicates that there is a need for an effective foundation ontology approach to support the provision of a set of reusable semantically-defined core concepts, which can be exploited by multiple domains.

Requirement 4. The ability to harness the appropriate semantic technologies in order to facilitate the explicit capture of domain semantics in computational form (formalisation) and to support shared meaning across domain models (i.e. domain ontologies and their related Knowledge Bases) constitutes another key requirement. This requirement can be broken down into a number of sub-requirements, the discussions of which are partly based on the challenges reviewed by [13].

Requirement 4a. Several families of knowledge representation formalisms have been developed represent ontology-based semantics. Such formalisms [14–16] altogether form a repertoire of languages in terms of their ability to represent semantics [17]. Consequently, there exists an ongoing need to understand which family of knowledge representation formalism allows the expressive capture and representation of product design and manufacture semantics.

Requirement 4b. Possible semantic mismatches that can exist between ontology-based domain models are diverse in nature [4, 18]. Examples of semantic mismatches, applied to the area of product design and manufacture, have been investigated [18]. The gathered understanding leads to a requirement for exploring semantic technologies able to improve the identification and resolution of possible semantic mismatches between domain models.

Requirement 4c. An essential stage in the reconciliation of domain models involves the capability to match across ontological content. A number of researched methods exploit the ability to formally specify cross-ontology correspondences as a means to establishing mappings from which ontology interoperability can be achieved [19–21]. However, at present, ontology mapping approaches still deserve attention so as to improve the capability for more effectively matching across domain models and verifying the integrity of mappings. Hence, a key requirement is concerned with the need for methods to explicitly and formally specify ontology matching relationships between domain models.

Requirement 4d. Performance is of prime importance in many dynamic applications, for example, where a user cannot wait too long for the system to respond [13]. Current methods for ontology matching may resolve from linear time to quadratic time, which may imply several minutes, hours or even days to complete a matching task [13]. This clearly indicates that the performance level of semantic reconciliation approaches proves to be an important asset which contributes to the strength of semantic technologies for supporting semantic interoperability. For this reason, a requirement is present to support higher performance levels as far as semantic reconciliation processes are concerned.

3 Framework

Figure 1 illustrates the explored framework, which has been proposed to satisfy the identified semantic requirements. The SMIF involves four constituent layers namely (1) a Foundation Layer, (2) a Domain Ontology Layer, (3) a Semantic Reconciliation Layer and (4) an Interoperability Evaluation Layer. The framework draws its strength from the combined application and improvement over selected methods and ontological underpinnings.

Overall, the SMIF contributes to (1) the understanding of ontology-based approaches to support semantic interoperability in product design and manufacture, (2) consolidating the knowledge behind the specification of a heavyweight manufacturing ontological foundation and the mechanisms involved in supporting the integrity-driven specialisation of domain models from the foundation and (3) defining semantic reconciliation methods that are pertinent to the evaluation and verification of correspondences between domain models that have been based on the same foundation, as a means to identifying interoperable knowledge.

3.1 Foundation Layer

The Foundation Layer provides a basis for sharing meaning and comprises two main elements namely (1) a Common Logic-based ontological formalism over which (2) a heavyweight manufacturing ontological foundation is constructed.

3.1.1 Knowledge Frame Language (KFL)

One of the key features of the SMIF, present in the Foundation Layer, is the Knowledge Frame Language. KFL is a Common Logic-based ontological formalism that provides expressive logic in which to encode the subject matter ontology [22]. Common Logic is a logical framework intended for information exchange and transmission and has some novel features, chief among them being a syntax that is signature-free, while preserving a first-order model theory [16]. This implies that KFL as a knowledge representation formalism is able to provide the necessary syntax and expressive first-order semantics to capture higher-arity relations and functions (in the ontological sense), as well as to support the semantic considerations needed in the other layers of the SMIF. The KFL formalism supports the motivation for new heavyweight ontological formalisms applied to the field of design and manufacture. This illustrates that the exploitation of the KFL formalism supports Requirement 4a.

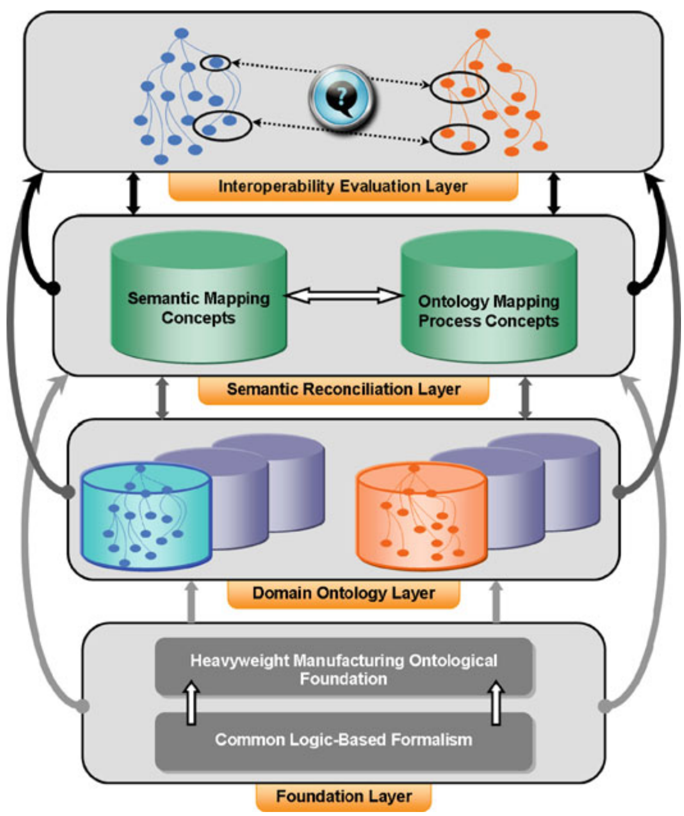


Fig. 1 Semantic Manufacturing Interoperability Framework (SMIF)

3.1.2 Manufacturing Ontological Foundation

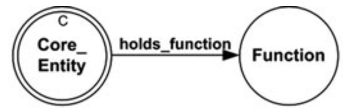
The heavyweight manufacturing ontological foundation rigorously represents entity information and process semantics together with essential relationships that hold between entities and processes in design and manufacture.

In order to capture entity information semantics, for the meaningful description of product-centric semantics, the fundamentals from the revised Core Product Model (CPM) [23] and those from ISO 10303 AP224 [24] are being exploited and adapted to the framework needs. This is because the CPM is a generic, abstract model that favours extensions in order to make the model readily expandable [23]. To improve the feature definition aspect, concepts from ISO 10303 AP224 are being adapted and formalised in the Foundation Layer to provide reusable mechanical product representation semantics.

Secondly, the accommodation of process semantics involves the formalisation of concepts from the Process Specification Language (PSL) [25]. The latter is available as an ontology written in the Common Logic Interchange Format (CLIF) and provides the necessary intuitions for the specification of manufacturing process semantics.

The combined approach of the CPM, ISO 10303 AP224 and PSL captures and integrates the semantics of concepts arising in several viewpoints such as the GD&T, design function and process planning viewpoints (Requirements 1 and 2). Furthermore, the rigorous yet extensible nature of the heavyweight manufacturing ontological foundation supports a novel understanding of foundation ontologies for manufacturing. This is evident from the level of granularity in the chosen set of semantically well-defined reusable design and manufacture concepts, which can be individually specialised in the Domain Ontology Layer. Consequently, the Foundation Layer helps to fulfil Requirement 3.

Figure 2 next illustrates two classes namely “Core_Entity” and “Function” bound by a relation “holds_function”, and defined in the heavyweight foundation. An example of a foundation IC written in KFL is shown. This IC is present to ensure the optional accompaniment of product functions and sub-functions during the definition of core entities. Core entities include, for example, artifacts (i.e. products or families of products) and the design and manufacturing features held by artifacts.




```
(=> (Core_Entity ?coreEnt)
    (exists (?func)
        (and (Function ?func)
            (holds_function ?coreEnt ?func))))
:IC soft "Every core entity holds some function"
```

Fig. 2 Example of foundation semantics

3.2 Domain Ontology Layer

The Domain Ontology Layer is at the second level of the SMIF. At this level of the framework, semantic structures from the Foundation Layer can be reused, extended and specialised for the construction of domain models. A number of ontological mechanisms are supported by the SMIF in order to allow domain models to be integrally defined. These are next discussed.

Contexts for identifying domain models. During the specialisation of domain models from the Foundation Layer, two separately developed domain models could be employing the same terms to mean different notions. At first sight this would lead to semantic conflicts. However, following the SMIF approach, domain models are built “within contexts”. “Contexts” are very similar to namespaces in the Semantic Web and are useful to (1) differentiate between elements and attributes from different vocabularies with different meanings that happen to share the same name [26] and (2) to group all related content from a single domain model together so that implementation platforms can easily identify them.

Ontological relationships and domain ICs. Figure 3 identifies examples of relationships that can exist between the first two levels of the framework in order to allow domain ontologies to be specialised in an integrity-driven way. Class subsumption relations can be defined in order to declare new classes in the Domain Ontology Layer. For example, the domain class “Locating_Hole” is made a sub-class of the foundation class “Round_Hole” (which is a defined concept adapted from ISO 10303 AP224). Ontological relations from the foundation such as “holds_function” can also be reused. On the other hand, ICs defined in the Foundation Layer ensure that domain models are not allowed to infringe critical foundation semantic structures. Domains can also develop their own ICs, as shown in Fig. 3, as long as these do not violate foundation ICs.

Discrete knowledge representation. In the Domain Ontology Layer, instantiation is the process of asserting facts (instances) and fact sentences (statements about how instances are related) to capture concrete states of a domain ontology in the KB associated to the ontology. Instantiation is a valuable process for the representation of reusable design and manufacture domain knowledge. The successful population of instances demands the satisfaction of all the related foundation and domain-specific ICs set over their classes. In this way, accurate and complete discrete knowledge can be captured for the domain ontologies that are being populated within the Domain Ontology Layer.

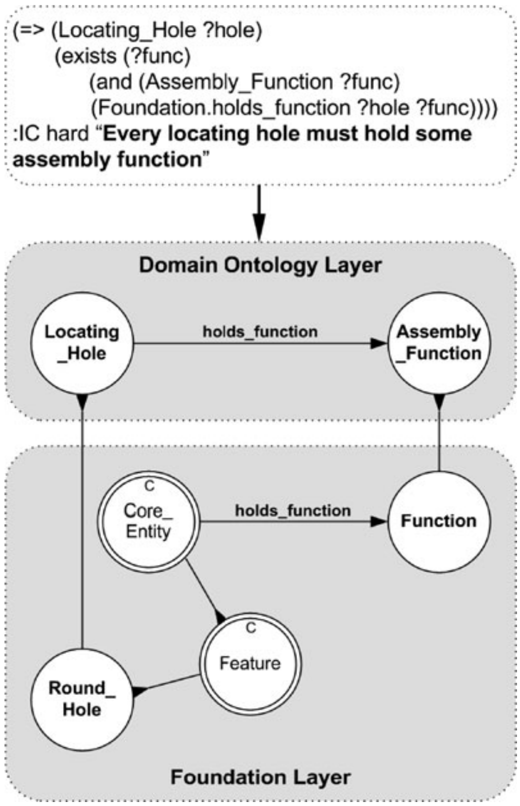


Fig. 3 Example of ontological mechanisms facilitating specialisation

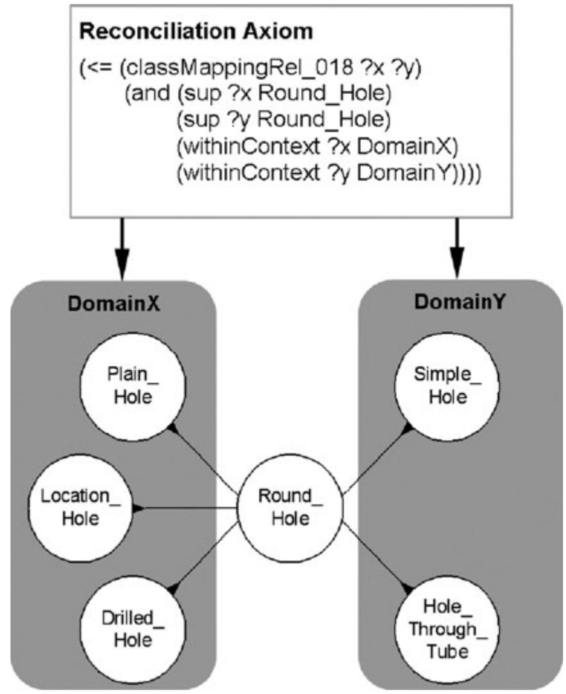


Fig. 4 Example of a semantic mapping concept

3.3 Semantic Reconciliation Layer

In a collaborative product development arena, several domain models are likely to exist in the Domain Ontology Layer, following the SMIF approach. In the event that these models need to interoperate with the intention of sharing knowledge, their semantic structures need to be reconciled. The approach to the reconciliation of cross-domain semantics pursued in SMIF consists of logic/rule-based ontology mapping methods.

This helps to tackle some of the current limitations of existing ontology mapping frameworks. In the third level of the framework, logic-based statements can be formulated to formally capture the conditions during semantic reconciliation. The capabilities of the reasoning mechanisms involved overtake those currently exploited by other ontological approaches. In this sense, the third level of the framework satisfies Requirements 4b to 4d.

Semantic Mapping Concepts. These concepts are formally-defined mapping relations, with tagged informal remarks for human interpretation. Semantic mapping concepts carry the nature of interoperable knowledge during the reconciliation of cross-domain semantics. Consider the class "Round_Hole" from the Foundation Layer (see Fig. 4).

This class has three specialisations in a "DomainX" ontology and two sub-class specialisations in a "DomainY" ontology. A logical statement could be written as a built-in semantic mapping concept to capture the following informal semantics: If the foundation class "Round_Hole" has sub-classes in "DomainX" and sub-classes in "DomainY", then, any pair of sub-classes of "Round_Hole" coming from "DomainX" and "DomainY" exhibits the commonality of being features of cylindrical or conical negative (removal) volume (this definition follows from the formal semantics of "Round_Hole" in the Foundation Layer).

This semantic mapping concept appears in the "Reconciliation Axiom" window in Fig. 4. The semantic mapping relation is denoted by the built-in "classMappingRelation_018" and the natural language information that it carries (here not shown) helps to capture the stated reconciliation condition. More complex logic-based statements can be formulated to establish intricate knowledge sharing scenarios arising at several levels of the structure of domain models.

Ontology mapping process concepts. The process of ontology mapping can be performed for two domain models at a time. The process comprises stages of loading two domain models into the same Object Management System (OMS). Following this, reusable semantic mapping concepts are loaded into the merged models. During this process, the relevant semantic mapping concepts are established between cross-ontological content based on deductive reasoning.

3.4 Interoperability Evaluation Layer

The Interoperability Evaluation Layer is where cross-domain correspondences, i.e. aligned mappings, can be retrieved in a semi-automatic way. The ability for so doing depends on the processed semantic mapping concepts established at the previous level of the framework. The ways by which the discovery of interoperable knowledge can be made involves the formulation of queries. Based on the example in Fig. 4, a query could be executed to find all semantic mapping concepts that hold between "Plain_Hole" and "Simple_Hole". The mapping concept "classMappingRelation_018" would become a logically verified correspondence between these two classes (Requirements 4c and 4d).

4 Implementation

The SMIF has been implemented using the Integrated Ontology Development Environment (IODE) V2.1.1 developed by Highfleet Inc. (formerly Ontology Works Inc.) [22], because this environment is capable of handling Common Logic-based semantic structures.

4.1 Foundation Layer

Figure 5 portrays the implemented Foundation Layer. A majority of the classes present in the taxonomy for the heavy-weight manufacturing ontological foundation is shown. The figure highlights the class "Round_Hole" and its informal description, together with the relations for which the class "Feature", and hence "Round_Hole", is an argument to. These relations include, for example, the unary relation "compound" for the statement of complex features that are composed of singleton features, and the binary relation "holds_feature", which is used to associate features to artifacts. Figure 5 also depicts two of the implemented ICs relevant to the class "Round_Hole".

4.2 Domain Ontology Layer

Figure 6 depicts a "Machining Hole Feature Ontology A" that has been specialised from the Foundation Layer (see taxonomy). The diagram illustrates the type of part family under consideration as well as some of the feature classes that have been specialised in the domain model.

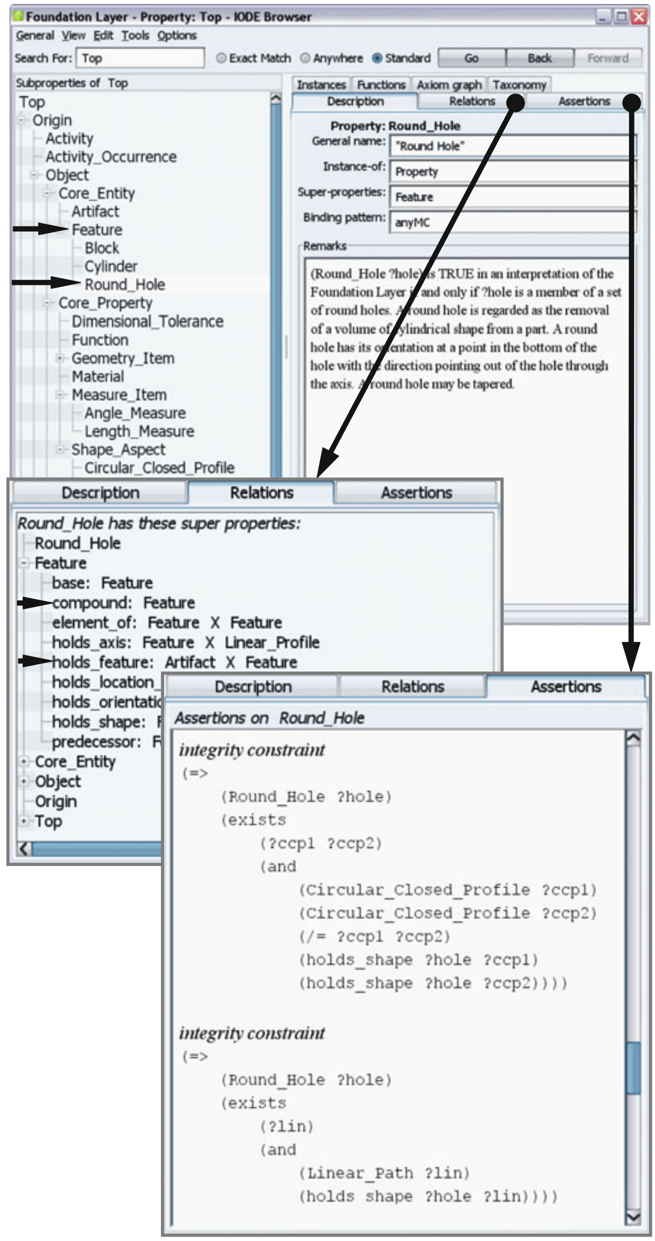


Fig. 5 Implemented foundation layer

During the development of this domain model, all the identified ontological mechanisms in Sect. 3.2 have been successfully employed towards its semantically-sound configuration (i.e. specialisation). The figure also shows a concrete state of the class "Reamed_Hole", named "Reamed_Hole_A", present in the domain model and carrying instance knowledge such as nominal sizes, diameter tolerances and related transition features.

Another individually-developed domain model has been implemented in a similar way as explained above. Figure 7 informally depicts "Machining Hole Feature Ontology B". This domain model is also developed from the Foundation

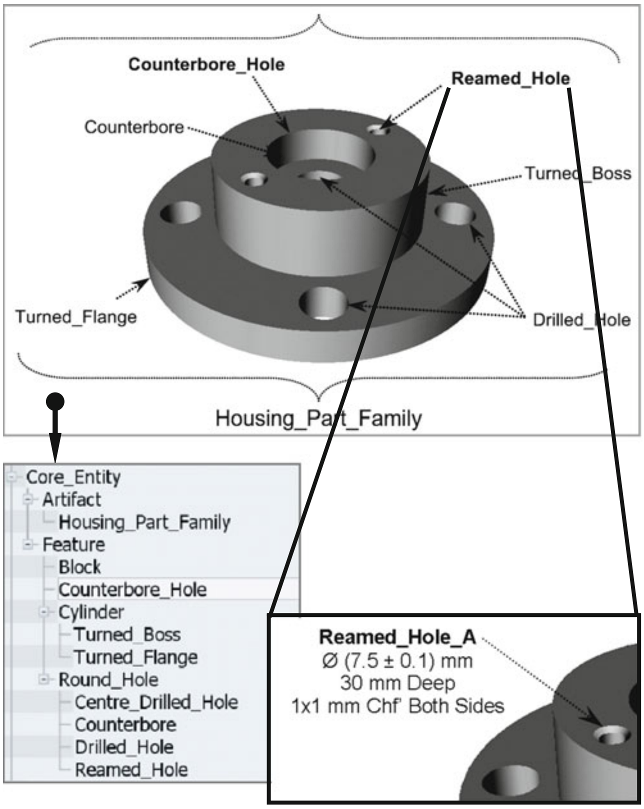


Fig. 6 Example of concepts explored in "Machining Hole Feature Ontology A"

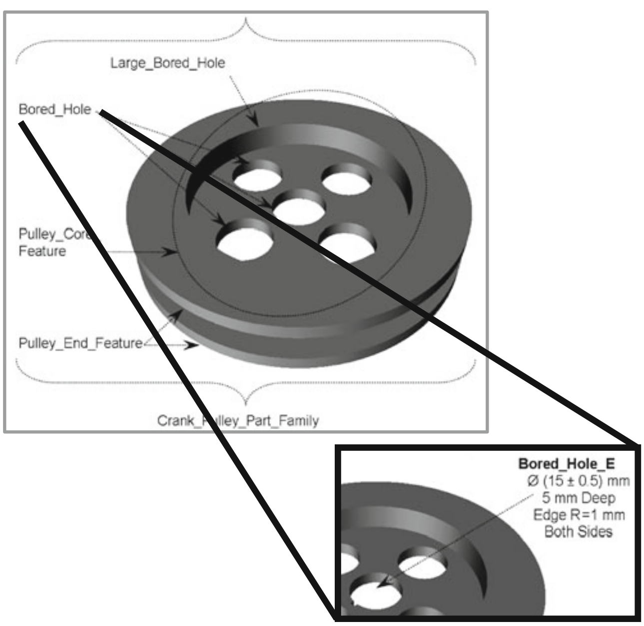


Fig. 7 Example of concepts explored in "Machining Hole Feature Ontology B"

Layer in an integrity-driven manner. The figure reveals the type of part family being represented and also identifies a concrete state (i.e. instance) of the domain-defined class "Bored_Hole". This instance named "Bored_Hole_E" holds important instantiated dimensional semantics.

To partly illustrate the semantic reconciliation capabilities of semantic mapping concepts defined in the Semantic Reconciliation Layer, the domain-defined classes "Reamed_Hole" and "Bored_Hole" are to be reconciled. Furthermore, to reveal semantic reconciliation at the instance level of domain models, an aspect which until now has proved to be relatively problematic, the correspondences that hold between the two declared instances "Reamed_Hole_A" and "Bored_Hole_E" are also to be discovered.

4.3 Semantic Reconciliation Layer

The Semantic Reconciliation Layer can then be deployed, following the ontology mapping process concepts explained in Sect. 3.3. This is required in order to achieve the reconciliation of ontology-based content from "Machining Hole Feature Ontology A" and "Machining Hole Feature Ontology B". The reconciled domain models can then be queried for semantic mapping discovery.

4.4 Interoperability Evaluation Layer

The Interoperability Evaluation Layer typically uses querying mechanisms for the retrieval of established semantic mapping concepts between cross-domain ontological content. A query tool facility provided in the ontological environment IODE supports the capability to effectively retrieve verified semantic mapping concepts. One query to find all semantic mapping concepts that hold between the classes "Reamed_Hole" and "Bored_Hole" has been processed. The result in Fig. 8 is successfully obtained (see "classMappingRelation_018"). This verified semantic mapping concept can then be browsed in order to view the informal implications of the relation, in the form of natural language statements or remarks. These statements are listed below.

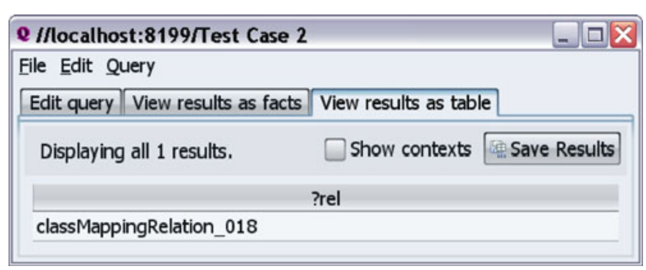


Fig. 8 Example of a query result

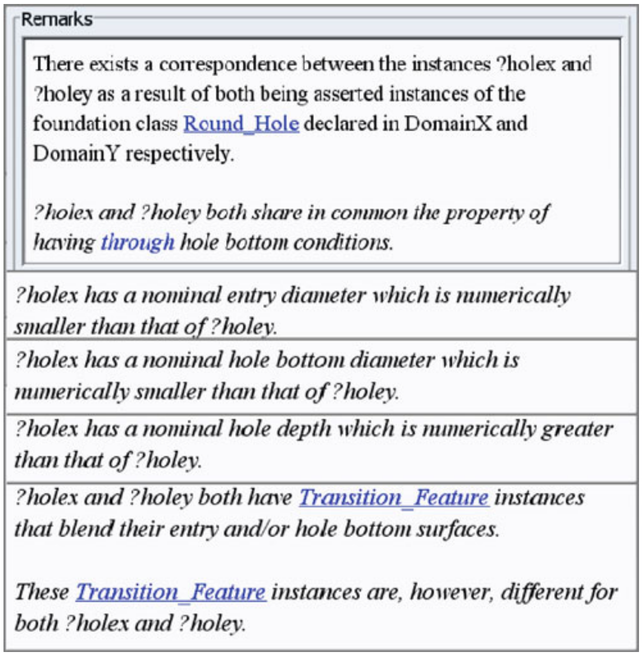


Fig. 9 Sample of retrieved correspondences between "Reamed_Hole_A" and "Bored_Hole_E"

General remarks. There exists a commonality between the class ?x in the "DomainX" context and the class ?y in the "DomainY" context as a result of both ?x and ?y being subclasses of the foundation class "Round_Hole". Both ?x and ?y capture the notion of a feature that is of cylindrical or conical negative (removal) volume.

Limitation remarks. Without reference to the terms assigned to the concepts ?x and ?y, there could potentially be class mismatches present. This is because ?x and ?y could have been defined with a view on specific domain preferences, which vary across domains.

It is to be pointed out, in this case, that the variables ?x and ?y in fact refer to the classes "Reamed_Hole" and "Bored_Hole" respectively. Also, it is important to notice the implications of the limitation remarks which convey essential informal reasoning on how it is not possible to infer commonalities between the two domain classes. Figure 9 then identifies a sample of five browsed results established between the "Reamed_Hole_A" and "Bored_Hole_E" (referred to as ?holex and ?holey in the browsed results respectively).

5 Discussions and Conclusions

Compared to other related approaches attuned specifically to semantic interoperability such as the eCOIN framework [27], the approach explored by [28] and that of [29], the SMIF has contributed to the identification and application of more formal ways for capturing knowledge, by starting from a low level of abstraction, such as the GD&T semantics required for the definition of product features in design and manufacture.

In addition to this, effective heavyweight methods have been investigated in order to achieve resolvable and meaningful interoperable knowledge sharing between domain models during. The interpretation of the interoperable knowledge, backed by tractable reasoning, overtakes the simple mapping relations used, for example, in OWL-based reconciliation and reasoning (where limitations to mapping relationships such as "equivalentClass", "equivalentProperty" and "similarTo" are found).

Recently, an initial proposal for a future SC4 architecture has been realised [30]. Interestingly, the structure of this architecture bears some striking similarities to the fundamental concepts explored in the SMIF approach. Observations from the researched concepts and implementation of the SMIF thus indicate that similar drivers are being considered by the ISO Standards community to support their future needs.

However, it is clear from the breadth of scope of this work, that it would be highly desirable to explore an extended manufacturing foundation ontology. Extensions would require capturing a set of product lifecycle concepts, together with other types of feature in relationship to the notion of design and manufacturing part families.

Acknowledgments The framework developed in this chapter has been supported through a research studentship funded by the Wolfson School of Loughborough University. We also wish to thank the EPSRC, who are funding the majority of our work on "Interoperable Manufacturing Knowledge Systems" (IMKS) under project 253 of the Loughborough University Innovative Manufacturing and Construction Research Centre.

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Knowledge Management for Innovative Design

J. Xu, R. Houssin, E. Caillaud, and M. Gardoni

Abstract Innovation is mandatory for the survival of industrial companies more than ever subjected to competition. For this reason it is crucial to help the designers to innovate faster and more efficiently than competitors. The aim of our study is to propose an approach for designers to facilitate innovation in innovative design. By analyzing the multi-disciplinary literature, knowledge management (KM) is regarded as a promising approach to support innovative design. The interactions between KM and innovation have been investigated. From a human centered perspective, we model KM for innovation by focusing on the more efficient creation and use of knowledge in design. A hierarchical model is constructed for leveraging KM activities into innovation. Finally, the applicability and usefulness of our approach is demonstrated through a software prototype being tested with an industrial partner.

Keywords Innovative design · Knowledge management · Meta-model · Knowledge lifecycle model

1 Introduction

Recently innovation as well as Knowledge Management (KM) in design has come into the forefront of scientific research in engineering domain. Moreover, knowledge has been increasingly considered as an essential resource for a company, thus it is crucial for companies to manage knowledge for achieving more innovations. Because of the circumferential changes of design, there is an increasing burden on designers to innovate new products [1]. To be able to innovate, KM appears as a possible way which needs to be profoundly studied. The research on KM is mainly performed from the perspective of management; while for innovation in design, it is largely performed in the point of view of engineering. In order to maximize profits and improve values of knowledge, linking KM to innovation becomes an important issue. As a consequence, how to support the innovation in innovative design through the approach of KM is the main problematic of our research.

On the one side, a large part of existing knowledge based systems and methods of KM appear in engineering field, which mostly focus on the reuse of knowledge and product improvements [2, 3]. Meanwhile, in the domain of innovation management, a lot of idea/innovation management systems have been created for ideation, innovation and its implementation, but the requirements of engineers in innovation are not well considered and supported in these systems [4]. On the other side, many computer-aided innovation systems have been founded on innovation theories such as TRIZ. They often depend on technical databases and patent bases, and require users to be familiar with problem modeling techniques. They are hard to use due to the difficulty of using general principles and laws in specific design situation [5] and their results are difficult to be integrated into design [6].

In order to understand the nature of our problematic, first the publications in both innovation and knowledge are reviewed, and their relationships are analyzed. Based on these analyses, we set up a systemic characterization of knowledge for innovation in order to capture its content and context. Later an interaction meta-model of knowledge creation and use and a knowledge lifecycle model are built for modeling the knowledge activities in innovation. A dynamic model of innovative design is illustrated. By integrating the above models, a hierarchical model is created to analyze and describe the interactions between KM activities and innovation in design. Finally, a software prototype based on these propositions is constructed and an application is previewed and being tested at a partner company specialized on sheet metal industrialization. The process of our research work presented in this chapter is illustrated in Fig. 1.

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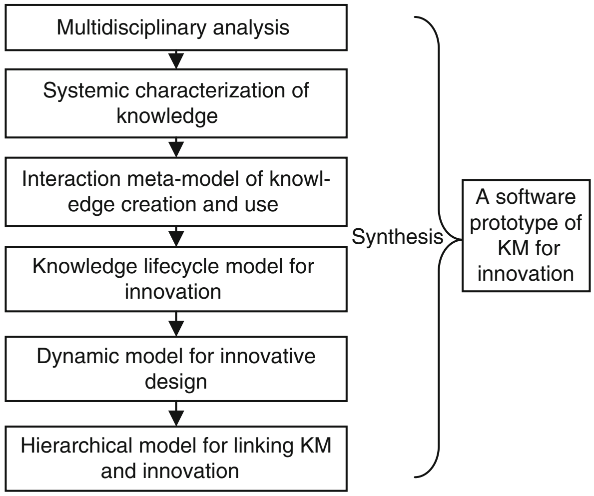

Fig. 1 Proposed process for a software prototype for innovation

2 Analysis of the State of the Art

In this section, both innovation and design are reviewed and their relationships are analyzed. Knowledge evolution and its relationship with innovation are discussed later with the identification of their new trends.

2.1 Innovation and Its Process

We remind that our study focuses on innovation from the engineering point of view. In this section we present the evolution of innovation concept from many points of view. Innovation becomes a research subject, which can date back to Schumpeter's statements in 1934. Originally, innovation is defined as the successful introduction of new things such as products, methods of production, market, etc. Innovation is defined as an object, a tool for entrepreneurship or an output of an enterprise from the perspective of management [7]. While in the field of engineering, innovation has been seen as a series of related activities from the initial raw ideas to the last commercial product in the market. In terms of the initial focus, there are product, process, organizational and marketing innovation [8]. According to its novelty, it can be classified into radical, really new and incremental innovation [9].

Innovation can be considered both as a process and as an outcome of this process. By reviewing a variety of innovation processes [10, 11], we argue that the interactions and iterations in the process are inevitable. The activities in the processes should be executed in a parallel and concurrent order. Further more it has been noticed that few processes pay attention to the activities after the diffusion of innovation. From the perspective of lifecycle and systems thinking, it is necessary to include one step of internalization that represents the activities after diffusion and capitalizes the knowledge created and used in innovation such as lessons learned and best practices for fostering more innovation. A general innovation process can thus consist of idea generation, research and development, prototype and manufacturing, commercialization and diffusion [11] and internalization.

Innovation could appear in different types of design such as the original design [12] or the innovative design [13]. The objects of design and innovation are similar, which are the product, service, process, system etc. According to C-K design theory [14], creative results are an integral part of design process, and design process is the dual expansion of concept space and knowledge space. Gero et al. [15] have located the possible innovations in various steps in the FBS (Function – Behavior – Structure) design process. Due to design as an activity more widely used than innovation, we focus on the type of innovative design that leads to innovation.

2.2 The Concept of Knowledge for Innovation

In the knowledge based economy, knowledge is more and more seen as a vital asset and the main source for innovation. However, because of its mysterious nature, there is no simple definition generally accepted. In literature, there exist several important views on knowledge as summarized in [16]. The epistemology has changed from a monist view to the pluralist one. Two common epistemologies are the objectivist [17] and the practice-based [18]. The objectivists consider knowledge as an object/entity, and focus on its explicitness. On the other hand, the practice-based one emphasizes the embeddedness of knowledge in human activity (practice).

In information and computer science, knowledge is different from data and information, but related to both of them [19]. A hierarchy of Data, Information and Knowledge (DIK) depicts the relationships among these concepts. Data and information are the basis of knowledge; with syntax and relations, data turn into information, and by adding meanings and patterns, information is converted into knowledge. Then knowledge helps human to make decisions and to take actions that generates new information and data as shown in Fig. 2.

Meanwhile, knowledge is intangible and often embedded in diverse kinds of assets as forms of organizational knowledge [7]. Due to the multifaceted nature of knowledge, many systems theories are used to explore its nature. Allee [20] proposes the wave-particle duality of knowledge from the analogy of light. Norris et al. [21] proposed that knowledge can be modeled as a "thing" and a "flow" at the same time. Nonaka et al. [22] build a continuum model of knowledge

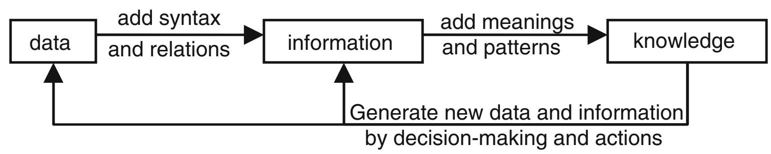

Fig. 2 Relationships of DIK hierarchy

including both the tacit and explicit contents. The problem of "Not invented here" is a major impediment of knowledge due to the trustfulness. Since knowledge is created and used in specific contexts for particular objectives, its dynamic context should be capitalized in order to better understand its ad hoc state and to increase its trustfulness. Thus, a systemic knowledge model for innovation should include both its content and context. We adopt the definition of knowledge in [19]: "knowledge is a mix of framed experience, values, contextual information and expert insight that provides a framework for evaluating and incorporating new experiences and information" and a knowledge model for innovation is created based on the above discussions.

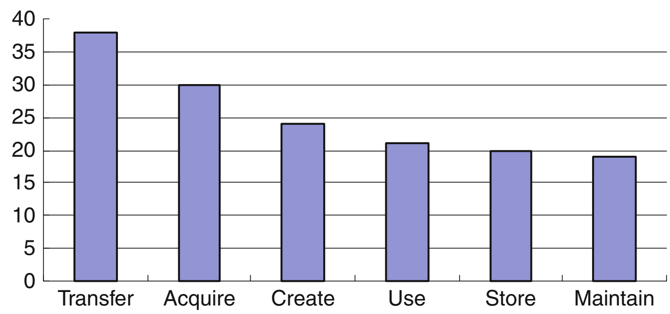

Fig. 3 Frequencies of KM activities in different groups

2.3 Core Activities of KM for Innovation

A large part of the research on KM in design and innovation focuses on the capitalization and reuse of design knowledge [2, 3, 23, 24]. Recently the issue of improving innovation in design has gained increasing attention [14, 15, 25, 26]. The approach of KM provides theoretical and practical foundations for managing knowledge to encourage more innovation. In this section, we distinguish the core activities of KM and a human-centered perspective for KM and innovation.

With the increasing emphasis on innovation and knowledge, a more fundamental need for a company is to understand how new knowledge can be created and used more effectively and efficiently in innovative design. By this means, new products, new methods of manufacturing, marketing and new organization forms can be achieved. Since Wiig [27] proposed the notion of "Knowledge Management", it has been studied from various perspectives with many approvals and critiques. From diverse perspectives, the focus of KM varies significantly. There are several generations of KM. In the first generation, it focuses on information processing and transferring, and then turns to the knowledge codification and reuse [27, 28]. In the second generation, KM focuses on the knowledge creation and sharing [29, 30]. In the next generation, KM focuses on the evolution of knowledge lifecycle and value creation of knowledge assets [31, 32]. However, the mechanisms of KM for value creation, especially for innovation are still under construction in the latest generation.

Among the different points of view of KM, the process perspective is popular in the engineering field and has advantages on the value creation and innovation performance [33]. In literature, about 40 processes and frameworks of KM [16, 19, 27, 29, 31, 32, 34] are reviewed and analyzed. It is noticed that a lot of diverse activities exist in these processes. In order to distinguish the core activities of KM, we synthesize the different activities with the similar function into six groups. The activities with their appearing frequency in all these processes are analyzed in Fig. 3.

From Fig. 3, it is obvious that activities of transfer and acquisition are widely recognized. While the creation and use do not gain enough attention in the specialized literature and their studies are unsystematic. They are analyzed systematically based on pioneering research.

Concerning the creation of knowledge, there are many efforts to explain the emergence of new knowledge that is essential to innovation. In pioneering research, the emergence of new knowledge has been interpreted as knowledge production [7, 35], knowledge creation [29, 30] and knowledge generation [19, 36] from different points of view. According to our analyses, we argue that knowledge production focuses on the static aspects of knowledge that is regarded as a product and embedded in artifacts. Knowledge creation considers knowledge as a process and capability, which is held by human and could be integrated in innovative design. Knowledge generation focuses on the codified knowledge embodied by technologies and methods used in design to produce artifacts.

Only when knowledge is used, can its value be fully realized. Thus knowledge use is also critical in innovative design. As a consequence, the creation of knowledge becomes a prerequisite for the usage. Landry et al. [37] studied the four models of knowledge use – the technological, economic, institutional and social interaction model. Through these models, the nature of knowledge use has been extended from a simple activity to an interactive process. In literature, knowledge utilization, use and application are not distinguished and used interchangeably. Based on our analyses, knowledge utilization focuses on the physical aspects of knowledge. Meanwhile, knowledge use is more about the mental aspects of knowledge concerning a particular situation. Knowledge application is often used when discussing KM system and it focuses more on the technological aspects of knowledge [16].

As knowledge in a company is distributed, the creation and use of knowledge often do not happen in the same place and at the same time. There is a gap between them; acquisition, transfer, storage and maintenance activities of KM are carried out to fill this gap. As illustrated in Fig. 3, the transfer and acquisition are most popular and well studied in existing KM processes. With the rapid development of information technologies, they are greatly facilitated.

In the analysis of the KM activities, we distinguish three different points of view about knowledge and its management. They are the physical, human and technological points of view. We argue that the human perspective dominates innovation in design and is complemented by the physical and technological points of view. According to Drucker's arguments in [7], innovation is about the application of knowledge to create novelty. Finally we conclude that knowledge creation and use are the two core activities for innovation in innovative design from the human point of view.

2.4 Interactions Between KM and Innovation

There is a general consensus that both the explicit and tacit components of organizational knowledge play an important role in innovation [20, 29]. That KM can help to promote knowledge creation and innovation is studied respectively at the theoretical and practical level. Theoretically, it is concluded that an integrated approach towards KM can help to maximize innovation performance for competitive advantage of a company [38]. Empirically, many case studies are performed, and possible techniques and frameworks for managing knowledge with innovation are proposed [39].

The interactions between KM and innovation should be analyzed in a systematic way. After careful examinations of the various models for innovation, knowledge creation and use discussed above, we notice that there are some similarities among them. Different models of knowledge creation and use correspond to innovation models as in Table 1 below. We realize that the separated research on knowledge creation and use should be unified into an integrated approach for innovation.

Table 1 Corresponding models of innovation, knowledge creation and use

Models of innovation	Models of knowledge creation and knowledge use
Technology push model (1950s–1960s)	Knowledge production (1960s)
	Technological model (1960s)
Demand pull model (1960s–1970s)	Problem-solving methods (1970s)
	Economical model (1970s)
Coupling model (1970s–1980s)	Data-information-knowledge model (1980s)
	Institutional model (1980s)
Parallel and evolutionary model (1980s–1990s)	SECI Spiral, Knowledge Pentagram System (1990s)
	Social interaction model (1990s)
Innovation with systemic integration (1990s–2000s)	Nanatsudaki Model (2000s)
	Systems approach (2000s)
Open Innovation model (2000s)	No correspondent model

3 Characterizing Knowledge for Innovation in Design

3.1 Knowledge Classification for Innovative Design

The three perspectives of KM: physical, human and technological points of view emphasize the different aspects of the multifaceted knowledge. In order to successfully manage knowledge for innovative design, we propose three types of knowledge embodied in different forms of resources as the following:

- Knowledge in artifacts: knowledge assets can be embodied in physical objects: documents, products and services. This type operates as both an input to and an output for research, development and production in a company, which is a basic source of competitive advantage;
- Knowledge in human beings: knowledge assets are held by human whether inside or outside a company. This can be said, for example, of the expertise, skills, and competences of the employees or customers. This type of knowledge is subjective and socially constructed emphasizing the embeddedness and heterogeneity of KM;
- Knowledge in technologies: knowledge assets are embedded in the methods and technologies used by companies such as the methods and processes for using machines,

computers and software. And it also draws close attention to the methods and processes used in design process.

Due to the increasing complexity of design objective and the specialization of knowledge, it is argued that no company can have all the knowledge for its innovation. To be successful in innovation, all the three types of knowledge from diverse sources should be managed systematically and ensure their creative integration in innovative design.

3.2 A Systemic Characterization of Knowledge

In order to explore the multifaceted nature of knowledge, the knowledge properties and user contexts are defined respectively in [40, 41]. In order to characterize knowledge for innovation, a model of knowledge is built on the content and context models as in Fig. 4.

The content model structurally stores the different attributes of knowledge and the context model can capture the particular context when knowledge is created and used. The dimensions of content and context models are closely related to the characteristics of innovation. With this model, knowledge flow and its network can be depicted and visualized according to these different dimensions such as novelty and usability or task and social context. Together with the new classification, the knowledge model forms the basis of KM and innovation and provides new ways of understanding the phenomenon of KM and new methods for implementing the different strategies of KM for innovation.

4 Modeling KM for Innovation in Design

In order to obtain the maximum values from the knowledge assets, it is necessary to turn more available knowledge into innovations through the approach of KM. However, due to the complex relationships between knowledge and innovation, few models are generally accepted as a framework for analyzing them. In the following, we propose an approach to analyze their comprehensive interactions from a human-centered perspective. Here, we model the multidisciplinary KM as the base of the integrated approach.

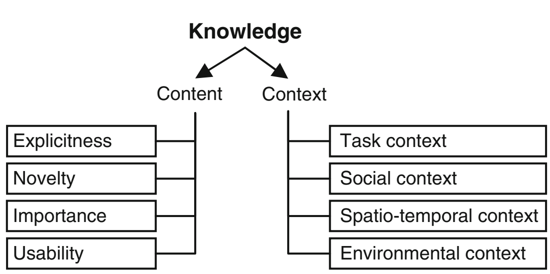

Fig. 4 Knowledge model with content and context

4.1 Interaction of Knowledge Creation and Use

Knowledge creation and codification do not necessarily lead to an improvement in performance, nor do they create values. The values of individual and organizational knowledge are embodied primarily in the application [16]. Due to the distributed nature of knowledge and the limitations of time and space, there are gaps between the creation and use of knowledge in a company. Since innovation is a result of the combination of existing and new knowledge [42], the seamless integration of knowledge creation and use is essential for innovation and its realization. The recombination of new and existing knowledge heavily depends on the activities of knowledge creation and use. Based on the above discussions, we propose a meta-model to present the interaction of knowledge use and creation for innovation in design as illustrated in Fig. 5.

The interaction meta-model is composed of the two core activities of KM for innovation: creation and use of knowledge, whose interactions create new knowledge for innovation. Exploration and exploitation in organizational learning are important for competitive advantage of a company [43]. Here, we consider knowledge creation as the exploration of the new knowledge and knowledge use as the exploitation of the existing. A well-defined balance between them will help to innovate efficiently and effectively [43]. In the model, we distinguish respectively the two aspects of knowledge creation and use: one for innovation and the other for non innovative activities [35, 44]. Knowledge creation has two senses: one is to create subjectively new individual knowledge just like individual learning, and the other sense is to create socially new knowledge. Both of the senses have the potential for innovation. Knowledge use also has two aspects, one is the creative and recombinative integration of existing knowledge for innovation, and the other is the replication of knowledge for routine tasks.

Because of the gaps between knowledge creation and use in reality, the interaction meta-model can be viewed as an ideal state of KM. In this state, the new created knowledge can be used without any impediments and new knowledge will emerge during the use of existing knowledge. This gap is seamlessly bridged by the intensive networking and system integration.

Based on the interaction meta-model of KM for innovation, we construct a knowledge lifecycle model in order to incorporate other activities of KM. We believe that two core

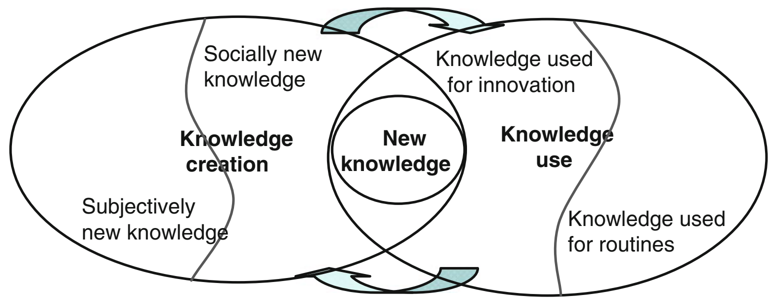

Fig. 5 Interaction meta-model of knowledge use and creation

activities: creation and use of knowledge must be supported and can be facilitated by other activities in the lifecycle model.

4.2 Knowledge Lifecycle Model for Innovation

According to the dominant human point of view of KM in innovation and design, a knowledge lifecycle should be able to describe the whole life cycle of KM and focuses on two crucial activities for innovation – knowledge creation and use. The proposed model is a prescriptive process, which consists of five phases: pre-creation, creation, intermediate, use and post-use as in Fig. 6.

The first phase is to define knowledge requirements, to search, acquire and retrieve existing knowledge whether it is inside or outside of a company and then to identify the gap between the requirements and existing knowledge. The second phase is the emergence of new knowledge, in which the creativity of human is crucial. The intermediate phase focuses on the retaining and spread of new and old knowledge, which acts as a channel between creation and use. In the phase of use, the new and existing knowledge is applied into practice to solve the design task and to inspect their validity. Finally, knowledge is refined and integrated for a new cycle.

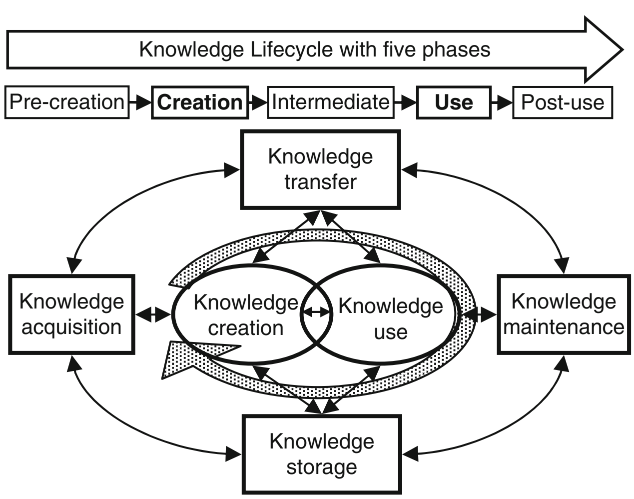

Fig. 6 Knowledge lifecycle model for innovation

As we have argued in above, the human perspective should be complemented by the other two perspectives: physical and technological. None of them should be neglected when implementing a KM project. They should work together in a collaborative and complementary manner. Different strategies for each perspective need to coordinate and collaborate with each other in order to enable the effective and efficient management of knowledge. The KM activities are linked together through the meta-model and executed concurrently. For example, in order to create new knowledge, the old knowledge not only needs to be acquired from the inside and outside of a company but also to be shared and stored.

The knowledge lifecycle model explains the management of organizational knowledge in a company at a macro level, while the interaction meta-model describes the crucial knowledge activities for individual knowledge at a micro level. The knowledge lifecycle model emphasizes on the integrity and lifecycle of KM in the innovation, while the interaction meta-model focuses on the human creativity and heterogeneity of knowledge for new ideas. During the process of KM, the individual knowledge manipulated by the meta-model will transcend its own boundaries into the organizational level where the knowledge lifecycle model dominates. We conclude that KM in a company is a dynamic process and its operation often takes place in a concurrent and collaborative manner. This leads to the hierarchical model of KM and innovation.

5 A Hierarchical Model for KM and Innovation

With the two quoted model of KM, we have obtained a more comprehensive understanding of this complex phenomenon. Here we will detail how innovation in design can be supported by our proposed models. For this aim, a dynamic model of KM for innovative design and a hierarchical model for KM and innovation are built. So that the activities of KM and the knowledge flow in innovative design process are visualized.

5.1 KM Dynamic Model in Innovative Design

Recently much research on innovative design has been done by focusing on the creativity aspects. We regard knowledge as the most important backbone of creativity according to the C-K design theory. Here, we attempt to model the innovative design process from the KM perspective. It is generally agreed that design is organized by different phases, and the most commonly acknowledged are planning and analysis of task, conceptual, embodiment and detailed design phases in [12]. Each phase arrives at a specific outcome and performs various tasks. In order to keep the general utility of our modeling, we think that design process can be viewed as the continuous and sometime iterative transition among these phases. From the point of view of KM, the transition can be modeled uniformly based on the interaction meta-model and knowledge lifecycle model. Considering the intensive iterations and feedbacks during the innovation, we propose that the iterations and feedback should be emphasized in this model as shown in Fig. 7.

The model illustrates the transition of a design phase from the design state Ds_i to Ds_{i+1}. The design state Ds_i is represented by an innovative design task with new needs of customers and new requirements. During each phase, designers generally perform several KM activities such as knowledge creation, use and integration. The transition first begins with search in knowledge bases in agreement with the inputs of the design task. Then according to whether there is available knowledge for the task, knowledge use and creation happen respectively. If the task is complex and it can only be partially solved, then integration between partial solutions is required. Finally, if the task is totally solved, design process transits into the next phase. If the task is not solved, the process returns to a reformulation of the design task and restart.

When the new needs are satisfied and new requirements are resolved through knowledge creation, use and integration, new design properties and knowledge appear in each

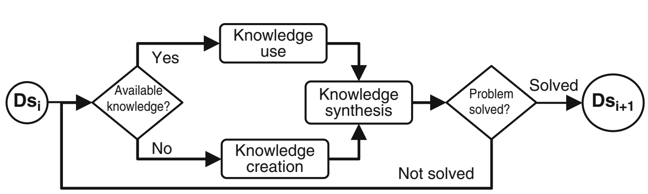

Fig. 7 Dynamic model of KM in innovative design

phase. As a result, this leads to the innovation in design. In the following, a hierarchical model is created for depicting the intensive interactions between KM and innovation in design.

5.2 Categorizing KM Activities for Innovation from a Human-Centered View

Information and Communication Technologies (ICTs) used actually in design process can not substitute human creativity. By analyzing the knowledge lifecycle model and interaction meta-model of KM, we find that human activities and information technologies have different effects on KM for innovation. Two categories of activities in the knowledge lifecycle model are identified.

- Knowledge creation and use consist of the first category, where human activities are of crucial importance. Human creativity, the heterogeneity and diversity of knowledge are keys to innovation.
- Other KM activities such as knowledge acquisition, transfer, storage and maintenance compose the second category, where human activities have been strongly weakened due to the extensive utilization of the ICTs and the wide building up of KM culture in a company.

The activities in the two categories also have different impacts on innovative design. The activities in the first category directly create values for innovation. Those in the second one facilitate and support knowledge flows in innovation and create a productive environment for it. The two categories need be organized into a hierarchical model for linking KM and innovation.

5.3 A Hierarchical Model for KM and Innovation

From the human-centered point of view, the two categories of KM activities manifest different natures of knowledge flow in innovation. Knowledge flow in the activities of the first category is slow and laborious because of the high intensity of human interventions and the low efficiency of the ICTs tools for them. As to other activities in the second category, due to the availability and convenience of ICTs, knowledge flow runs rapidly and easily. A hierarchical model with four layers is constructed in order to depict knowledge flow among KM activities and the innovation process as shown in Fig. 8. The four layers are distinguished according to the

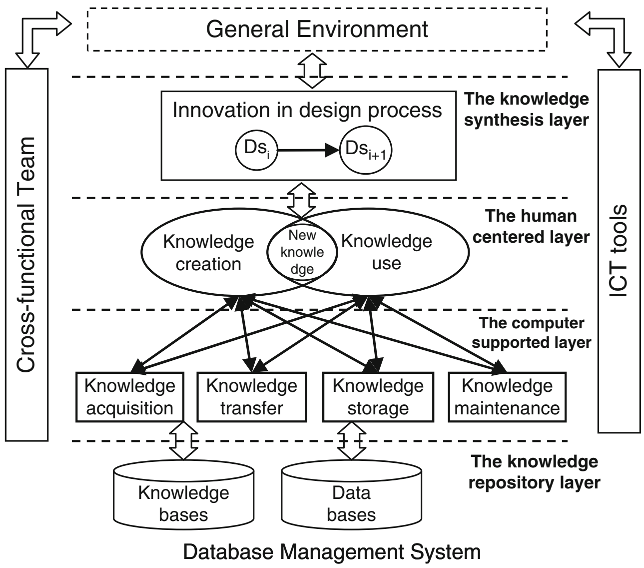

Fig. 8 The hierarchical model for KM and innovation

sequence and nature of knowledge flow in innovation. They are the knowledge repository layer, the computer-supported layer, the human-centered layer and the knowledge synthesis layer.

The knowledge repository layer contains knowledge bases used in innovation. In computer-supported layer, the acquisition, transfer, storage and maintenance activities are arranged. Different types of knowledge are retrieved and processed in this layer, then flow into the upper layer. Then, knowledge creation and use are positioned on the human-centered layer. In this layer, the interactions of knowledge creation and use lead to emergence of new knowledge for innovative design. Innovative design process is organized on the synthesis layer, where new and existing knowledge are synthesized and its values are embodied and realized. Finally, the knowledge created and used in the innovative design process flows back to the knowledge repository layer for a new cycle.

Because of the multidisciplinary natures of KM and innovation, they are both dynamic and interactive with the environment. In innovation, different people with different skills are required. It is necessary to have the right people with the right skills at the right time and place [45]. So a cross functional team consisting of diverse stakeholders for innovation should be integrated into the hierarchical model as one pillar. The cross functional team not only provides a physical space to communicate and collaborate, but also create an innovative climate and a culture to encourage innovation. There are many existing ICTs tools aiming for KM and innovation, which forms another important pillar in the model. ICTs provide convenience for the communication and collaboration between individuals and groups, and ease the human efforts in KM and innovation.

This hierarchical model is an integration of the knowledge lifecycle model and the interaction meta-model of KM with the help of cross functional team and ICTs tools. The focus on knowledge creation and use with ICT tools shortens the gaps between them and improves the efficiency and effectiveness of KM. It makes possible for individuals to enhance their creativities and to concentrate on the value creation for innovation.

6 A Software Prototype for KM and Innovation

Based on our proposed models, we first model the theoretical propositions by using Unified Modeling Language (UML). A partial static class diagram of UML models is shown in Fig. 9. Kn_agent represents an agent who helps to facilitate the KM activities of a designer. Kn_Element is a computational model of knowledge, which consists of the content and context model together with its basic attributes. Kn_Elements are managed by a graphic interface (Kn_Network_GUI) and stored in knowledge bases. Other models and diagrams are constructed for the prototype.

To ensure the traceability of knowledge, the object-oriented technology is applied to capture both the content and the context of knowledge creator and user, and then store them in Kn_element. For timely communication and trustfulness of knowledge, agent technology is also used for the evaluation of knowledge. At the same time, visual graph techniques are applied for a complete visualization of knowledge network. Java language is selected for implementing the prototype based on the client/server architecture.

A prototype of KM system for innovation has been developed and some of its interfaces are shown in Fig. 10. It is composed of several interfaces: login, agent management, knowledge audit and knowledge network etc. It provides a visual way for KM activities in innovative design, so that designers could find all available knowledge concerning the subject of innovation. And new relationships of existing knowledge could be deduced automatically for innovation by using the graph visualization technique. In this way, more innovation can be achieved in design.

This prototype for promoting innovation is being tested with a partner company specialized on sheet metal products. This test is in its first phase to implanting knowledge used by the professionals of this company. Some new knowledge elements are created in an innovative design project of a progressive mould for a sheet metal part as shown in Fig. 11.

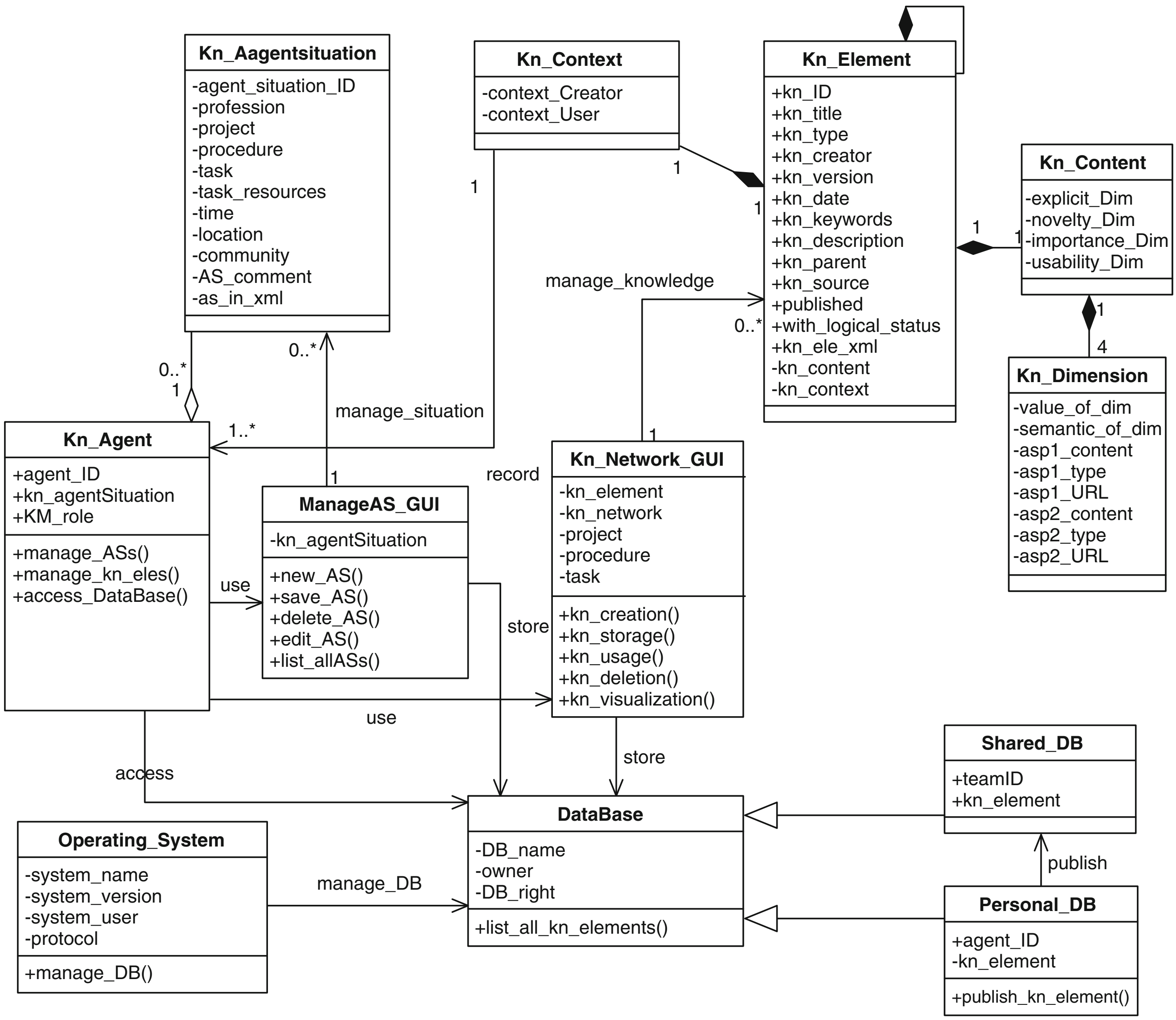

Fig. 9 Partial UML model of the system

With the initial results and feedbacks from our partner, more visualization functions and the algorithms of knowledge reasoning in the prototype will be improved by identifying the more detailed specifications for KM and innovation according to the requirements of the company. This system will cooperate and interact with the existing information systems in companies such as the CAD systems and PLM system in order to be more robust.

7 Conclusion and Perspectives

In this article, to facilitate innovation in design we have depicted the current situations and the difficulties in these fields based on the analyses of multidisciplinary literature. According to these analyses of innovation and KM, we construct an integrated approach of KM to illustrate how the KM approach can be used to support innovation in design.

We distinguish a human-centered point of view of KM for innovation, which is complemented by two other points of view: the physical and the technological perspectives. A systemic knowledge model for innovation is proposed. An interaction meta-model and a knowledge lifecycle model are built up to explore the roles of KM for innovation. They explain the KM phenomenon and analyze the interactions between KM and innovation at the micro and macro levels. With the proposed KM approach, a state transition model of innovative design process is built and a hierarchical model is set up for the integration of KM with innovation. Through it, the knowledge flow and the influences of cross functional

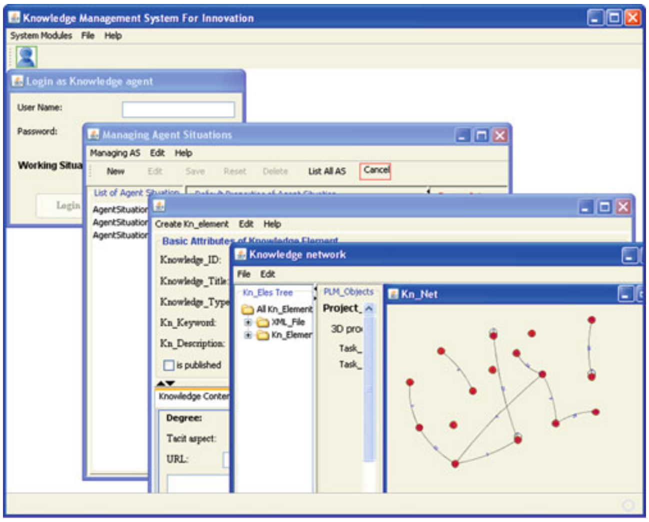

Fig. 10 Interfaces of the prototype for innovation

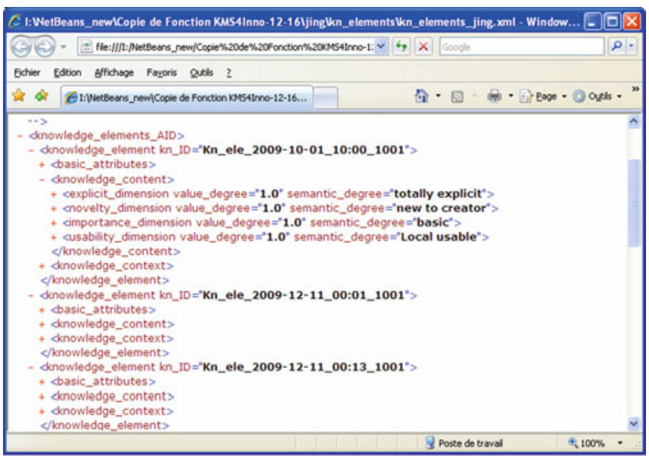

Fig. 11 New knowledge elements in XML format

team and ICTs tools for innovation are analyzed and visualized. Finally, a prototype of software on development is briefly presented. With reference to the initial feedbacks, new functions and algorithms will be developed and incorporated into the prototype. The details of our application at our industrial partner and the validation of developed software will be the subject of future research.

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Acquiring Innovative Manufacturing Engineering Knowledge for the Preliminary Design of Complex Mechanical Components

S. Mountney, R. Roy, and J. Gao

Abstract This research is concerned with the identification and sharing of the knowledge required during preliminary design when the manufacturing process is in development. An investigation was undertaken using a complex mechanical component with an innovative manufacturing process. The designers and manufacturing engineers involved in the preliminary design were interviewed and the data analysed. The difference in knowledge requirements depending on the domain specialism emerged as a significant finding. A schematic diagram to illustrate the knowledge interactions between the specialist domains was created. This will be used to create a methodology to facilitate the identification and sharing of manufacturing knowledge requirements.

Keywords Knowledge sharing · Innovative manufacturing processes

1 Introduction

A complex mechanical component is a component in a large product assembly which has mechanical, electrical and software sub-systems. Such a component is often complex in geometry and has to satisfy a number of design requirements from multiple specialist domains. Hence, a trade off is required. Such components are an example of adaptive design, where the component will be an adaptation of an existing configuration. This design process is typically managed with a systematic process with three phases: concept, preliminary and detail design. Each phase of the process has its own knowledge management challenges: this research is concerned with the preliminary design phase.

During the preliminary design phase an initial physical engineering design solution is produced to meet the design specification generated during the concept stage. This physical solution typically shows the overall product sizing, the sizing of major components and the assembly interfaces between them. However, the geometry of each component has not been completely finalised at this stage. Amongst the different analyses which must take place to determine the final optimised solution, an initial decision about the manufacturing process and its feasibility must take place.

In certain situations it may be advantageous to consider using an innovative manufacturing process. For the purposes of this research, an innovative manufacturing process is defined as a manufacturing process which has not yet been applied to a particular component and material within the organisation. Consequently the manufacturing process is in development. Using such a process can be beneficial in that it can ultimately change the component configuration which can be achieved and better satisfy the other design requirements as a consequence. However, incorporating such processes can carry a risk in terms of the nature of the knowledge required to assess the feasibility. Because the process is in development, the knowledge is immature and as a consequence more tacit in nature and difficult to codify and share. Therefore the successful identification, acquisition and sharing of the knowledge represents a knowledge management challenge.

This chapter discusses a case study which was carried out to identify the manufacturing knowledge requirements for such an assessment. The example component featured is a blisk component used in the manufacturing of gas turbine engines for the civil aviation market.

2 Background

The engineering design process can be seen as a knowledge management process [1]. Defining the knowledge required

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for the engineering design process depends on three things: how the knowledge is defined, the knowledge content and the stage of the design process for which the knowledge is required.

The knowledge content required during the engineering design process depends on the engineering specialism being considered. Manufacturing knowledge has been defined as knowledge about the manufacturing process, its cost and its capability [2]. The content depends on the stage of the design process. Mostly the content required has been defined for the detail design stages when a detailed manufacturing assessment is due to take place. The content required for earlier stages of the design process has been described as being "more abstract" but has not really been defined [3, 4].

There are two definitions of knowledge which have been primarily applied to the engineering design process. The first is the data- information – knowledge hierarchy (as an example see Young et al. [5]). Here, data is described as text or numbers, information is data with added context and knowledge is an interpretation of information to give meaning. The second is tacit and explicit knowledge [6]. This definition sees knowledge belonging to and being generated by an individual and having two elements. Explicit knowledge can be codified and transferred, whereas tacit knowledge refers to the knowledge which is acquired by personal experience and is difficult to codify and therefore transfer. These definitions govern two approaches to knowledge management which have been defined as the commodity and community approaches. The commodity approach is governed by the data-information-knowledge hierarchy definition and views knowledge as something which can be subdivided into data and information which can be transferred outside its original source. This approach governs the development of information systems for knowledge management. The community approach governs tacit knowledge. This knowledge cannot be transferred because it cannot be codified: consequently, social mechanisms are used to transfer the knowledge between individuals within an organisation. Both approaches are relevant to engineering design as highlighted by McMahon et al. [7]. Approaches such as communities of practice and CSCW methods were seen as supporting tacit knowledge sharing, whereas information systems, ontologies and knowledge-based engineering systems were seen as supporting explicit knowledge transfer.

The challenge of sharing manufacturing knowledge during the design process has largely been treated in research using commodity approaches. The sharing of manufacturing knowledge during the design process is viewed as an interoperability problem: the standardised definitions are created in order to be understood by a series of integrated information systems. The methods used have been features (for examples see Maropoulos et al. [8], Sharma and Gao [9], Brunetti and Golob [10] and Bronsvoort and Noort [11]), information models (Young et al. [12], Canciglieri and Young [13]) and ontologies (Young et al. [14], Bradfield and Gao [15]). The techniques concentrate on defining a standard set of knowledge which can be comprehended by both the design and manufacturing domains. Although features are created to convey engineering information, they are created from the geometry of the component; consequently the geometry must be defined in order to define the feature. Information models widen the scope of manufacturing information beyond features (although they can also include features), however in order to define the models, the knowledge must be codifiable. These techniques have proved to be highly effective, especially in the detail stages of design where the geometry is fully defined and the manufacturing processes are well-defined and capable. However, where this is not the case, for example with a manufacturing process in development, other approaches are required.

Bohn observed that knowledge moves from a tacit to an explicit state as a process developed, i.e. the knowledge matures [16]. Therefore the ability to handle immature – and consequently tacit – knowledge is essential in improving knowledge management techniques during innovation. Therefore a new perspective is added to the manufacturing knowledge required during the preliminary design process for complex mechanical components. In addition to process, cost and capability, an indication of the maturity of a manufacturing process must also be included [17]. Cross-functional knowledge sharing is also seen as being critical for innovation, particularly for new product development. However, this in itself can prove a challenge due to different "thought worlds": differences in the way specialist domains perceive their and other domain's knowledge requirements [18]. Here, the community approach of knowledge sharing becomes important. Within the engineering design process, techniques used for tacit knowledge have been communities of practice, which are useful for generating knowledge sharing within the same domain of specialism and cross-functional teams, particularly Integrated Product Teams and other similar teams used in concurrent engineering practices [19].

The aim of this research is therefore to investigate how innovative manufacturing knowledge for the preliminary design of complex mechanical components can be effectively identified, acquired and shared. It considers a combined commodity and community approach to be a suitable knowledge management approach for this particular case. Hall and Andriani and Carlile adopted such an approach to assess the explicit and tacit knowledge required and cross-boundary knowledge sharing respectively in new product introduction [20, 21], however in terms of preliminary engineering design, and the sharing of manufacturing knowledge during preliminary design, this remains a subject for further investigation.

3 Knowledge Requirements

The nature of manufacturing knowledge for preliminary design was previously investigated [17, 22, 23]. The resulting conceptual framework, a foundation for this chapter, can be seen in Fig. 1.

The manufacturing knowledge required is defined by a "manufacturing impact". Initially the function of the component determines the material from which it can be manufactured. The material selection then determines the manufacturing process. The selected process impacts on the configuration of the component – its achievable size and shape. Although other engineering analyses (such as stress and thermodynamics analyses) will also have implications for the configuration which can be achieved, in this work the manufacturing process is seen as ultimately determining whether such a configuration can be realised. Hence the manufacturing process has conventionally been viewed as a constraint.

The manufacturing impact can be expressed depending on the maturity of the manufacturing process. If a process is in development, the expression of the impact is defined as being "empirical". Consequently, the configuration boundary is defined by specialist assessments based on current experience and development trials. As the process matures, these impacts become more "quantified" in that definite geometric limits can be applied to the component. Finally, the range of these geometric limits can be defined further to ensure that a pre-determined process capability is achieved repeatedly for the component: at this level the manufacturing impact is defined as "standardised".

A range of knowledge types are required to describe the expressions of impact. Structured knowledge is numerical or graphical and can be shown and transferred without context. Semi-structured knowledge is numerical or text based and contains additional context, however it is transferred in a codified manner (through written documentation). Unstructured knowledge is also numerical or text based with added context, but is transferred socially (via social meetings or telephone conversations) through informal social networks constructed by the preliminary design engineers during their years' experience with the organisation. These knowledge categories can be seen as examples of explicit (structured and semi-structured knowledge) and tacit (unstructured knowledge) knowledge. The conceptual framework highlighted the need for the inclusion of innovative manufacturing knowledge during preliminary design. It also confirmed the need for a combined approach to manage both the explicit and tacit knowledge requirements in reflecting the maturity of a manufacturing process. It also highlighted how the conventionally perceived constraint of a manufacturing impact can also be viewed as an opportunity. If a new manufacturing process is developed, this new process could alter the boundaries of the configuration envelope in a way that would mean that the design specification can be better satisfied. Although this offers a design advantage, the introduction of a process during development does carry a risk in the immaturity of the knowledge. Therefore this knowledge needs to be effectively identified and acquired in order to mitigate the

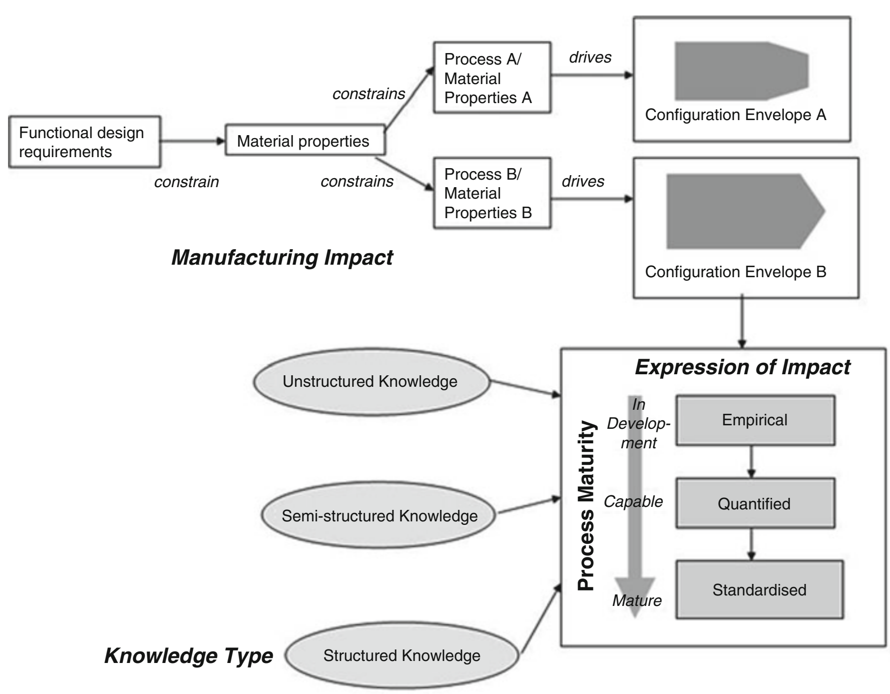

Fig. 1 A conceptual framework of manufacturing knowledge in preliminary design [17]

risk. The conceptual framework is therefore a useful illustration of the requirements for manufacturing knowledge for preliminary design, however it does have limitations, primarily its abstract nature. Further investigations were therefore required to find out how the conceptual framework would apply to an example complex mechanical component. A comparison of the knowledge for an innovative and a mature manufacturing process was also required. A suitable component was therefore selected which reflected these issues and examined in detail as a case study.

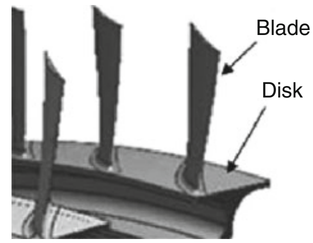

Fig. 2 Example of a blisk assembly

4 The Case Study

The blisk is a component which can usually be found in the compressor stage of a gas turbine engine which is used as an alternative to the conventional blade and disk assembly (see Fig. 2). The advantage of the blisk is that it is a single component and therefore does not contain the complex features required at the blade and disk interface to secure the assembly, so therefore contains less weight. This reduced weight offers advantages for the compressor rotation speed, operating temperature and ultimately the engine performance.

There are two manufacturing processes available for blisks. Conventionally these components have been machined from solid. As the size of the components increase this becomes a less cost-effective method. Consequently the larger components are treated as an assembly and are joined by linear friction welding. Machining is a stable and mature process. Linear friction welding is a process still under development, however its existence has enabled

Table 1 Summary of contacts for data collection activity

Contact	Department	Specialist domain	Range of knowledge
1. Preliminary mechanical designer	Concept/preliminary design (whole engine)	Preliminary mechanical (whole) engine design (Preliminary design stage)	Knowledge of the component (in terms of overall system architecture), overall understanding of some of the (mainly historical) manufacturing processes.
2. Designer	Sub-system design	Initial blisk manufacturing assessment (Preliminary design stage)	Detailed knowledge of the component, a more detailed understanding of the manufacturing processes available (current, historical and future) and factors influencing decisions for their use.
3. Manufacturing technologist	Manufacturing technology	Manufacturing specialist – machining from solid (Preliminary design stage)	Some knowledge of component requirements, detailed knowledge for specific manufacturing (or joining) process.
4. Manufacturing technologist	Manufacturing technology	Joining specialist – linear friction welding (Preliminary design stage)	Some knowledge of component requirements, detailed knowledge for specific manufacturing (or joining) process.
5. Tool designer, linear friction welding	Sub-system design	Specialist in tool design for linear friction welding process. (Preliminary – detail design stages)	Some knowledge of component requirements, detailed knowledge for specific manufacturing (or joining) process.
6. Manufacturing Engineer, linear friction welding	Sub-system design	Specialist in linear friction welding process. (Preliminary – detail design stages)	Some knowledge of component requirements, detailed knowledge for specific manufacturing (or joining) process.

blisks to be designed for larger engine configurations. This component and its processes were therefore an ideal case to be explored in detail. Six specialists were identified who were involved in the manufacturing assessment of the blisk. They were involved across a range of stages in the design process (Table 1), however for this case study the focus was on the knowledge required during preliminary design to enable a manufacturing assessment to take place. An interview was held with each of the specialists to discuss the manufacturing knowledge requirements for the blisk. These interviews were unstructured to allow flexibility in the topics covered and cover all appropriate topics. Notes were taken for each interview.

Each set of interview notes was then thematically analysed and the data categorised into the knowledge requirements and the rationale for the requirements. Validation of the data captured took place through peer feedback via a follow-up interview with each specialist for verification and by data triangulation with a technical report to outline the linear friction welding process which had been written in 2001.

5 Results

The data collection exercise for the blisk was initially expected to be straightforward, during which common manufacturing knowledge content would be acquired and agreed by all the specialists. Conversely, it was found that there was quite a significant variation in the knowledge requirements between the specialist domains.

Although all domains contributed to the manufacturing assessment of the component, each domain had its own individual concern. This concern could be expressed as a guiding question which then shaped the subsequent knowledge requirements. This is illustrated in Fig. 3. From each set of interview notes, the criteria needed to answer each guiding question was deduced. This is shown in Table 2.

Table 2 shows that despite each domain having its own concern and guiding question, each of these concerns were related to those required by the other domains. For example, in order for the preliminary manufacturing decision domain to reach a decision for the method of manufacture, the appropriate methods of manufacture to be explored must first be known. This depended on the decisions made by the preliminary mechanical design domain as to the actual nature of the component (blisk component or a conventional blade and disc assembly). This decision is governed by the performance specifications stipulated for the engine from concept design. Once the decision has been made for the method of manufacture to be used, this is then passed on to the preliminary manufacturing assessment domains for the selected manufacturing process.

The different concerns and guiding questions for each domain demonstrate that each domain has different knowledge requirements. These are interpreted as being examples of different "thought worlds" as outlined by Dougherty [18]. It is proposed that the combinations of these thought worlds are necessary to fully assess the component and arrive at an optimum solution for the method of manufacture. Although each domain has its own concern, the common objective for all the domains is to achieve this. It was therefore necessary to further study the interaction between these domains.

6 Study of Domain Interaction

A schematic diagram was created to illustrate the knowledge required for each domain and the interactions with other domains necessary to build this knowledge, according to the

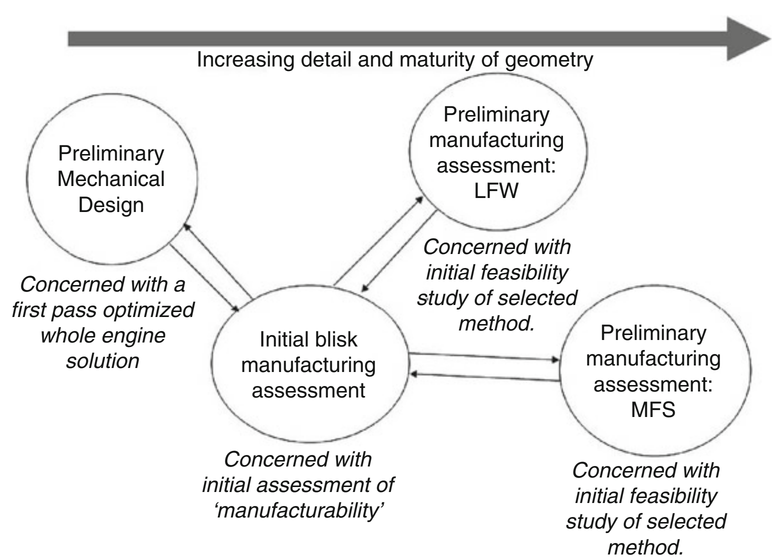

Fig. 3 Acquisition and sharing of knowledge: domain concerns and interaction during preliminary design process

Table 2 Initial analysis of concerns, guiding questions and criteria for each specialist domain

Specialist domain	Concept design (from preliminary design interview)	Preliminary mechanical design	Preliminary manufacturing decision	Preliminary manufacturing assessment: LFW	Preliminary manufacturing assessment: MFS
Concern		Concerned with a first pass optimized whole engine solution	Concerned with initial assessment of "manufacturability"	Concerned with initial feasibility study of selected method.	Concerned with initial feasibility study of selected method.
Guiding question	What are the engine design trends?	Do you want a conventional blade/disc assembly or a blisk?	What method of manufacture will be used?	What machine is this going on?	What machine is this going on?
Criteria required to answer question.	Core size is reducing (geometric constraint) Core speed is increasing (higher hoop stress at rim)	*Well defined* Available geometry (from core size) Rim hoop stress (from core speed) Weight *Not so well defined* Repairability "Manufacturability" (Method of manufacture, capability and maturity) Manufacturing cost.	What's the configuration envelope? (available geometry) There is a convention on the method of manufacture for particular compressor stages depending on the geometry. Decisions driven by relative cost of one method to another (as it's based on material removal) What materials?	Forge load (requires specific dimensional knowledge to calculate). Machine dimensional constraints. What materials are to be welded? What's the maturity of the process? Has this been done before?	Assessment of geometry of component is required, both in its raw ("condition of supply") and finished forms in order to assess best machining centre fit and tooling access. Material is also important to assess the most suitable tooling inserts for cutting.

rationale of each specialist domain. The schematic diagram shows a set of questions for each domain which must be answered to acquire the manufacturing knowledge for that domain.

It was created from analysing the manufacturing knowledge for each specialist domain. A series of questions required to answer the guiding question was deduced from the original guiding question. These in turn were sub-divided further to deduce more questions. The end result was a collection of concerns and questions derived to acquire the relevant manufacturing knowledge at several levels. These levels could be divided into component strategy, specialist process strategy, sub-process strategy and parameters and constraints for the sub-process strategy level. As with the data collection, the schematic diagram validated through peer review and feedback.

A section of the schematic diagram is shown in Fig. 4. Two significant features were found: the first was concerned with the granularity (increasing detail) of the required knowledge and the second was concerned with the maturity of the knowledge.

As the preliminary design process progresses across the different specialist domains, the need for more quantifiable knowledge increases in order to specify the criteria and answer each guiding question. This is illustrated in Fig. 4 by categorising the manufacturing impacts.

At the specialist process level, the concern is with the manufacturing requirements for the component, consequently the manufacturing impacts can be categorised as configuration impacts. With this type of the impact, the designer is aware of how a selected manufacturing process will constrain the configuration of the component, but not of the manufacturing reasons for this. As the knowledge sharing focuses more on specific manufacturing process and sub-process strategies, the manufacturing impact can be categorised as a tooling impact. This explains that the configuration of the component is limited by the machine tool dimensions and allowances need to be made in the design for this. This knowledge is held by the manufacturing expert but not the preliminary designer. Therefore there is a dichotomy in the knowledge: within the more detailed specialist manufacturing assessment domains, there is a requirement for the preliminary designers to provide knowledge which is more quantified. In the cases where there is a method of manufacturing in development, this represents a challenge. The knowledge required may not be mature enough to quantify the tooling impact. Additional development work may be required.

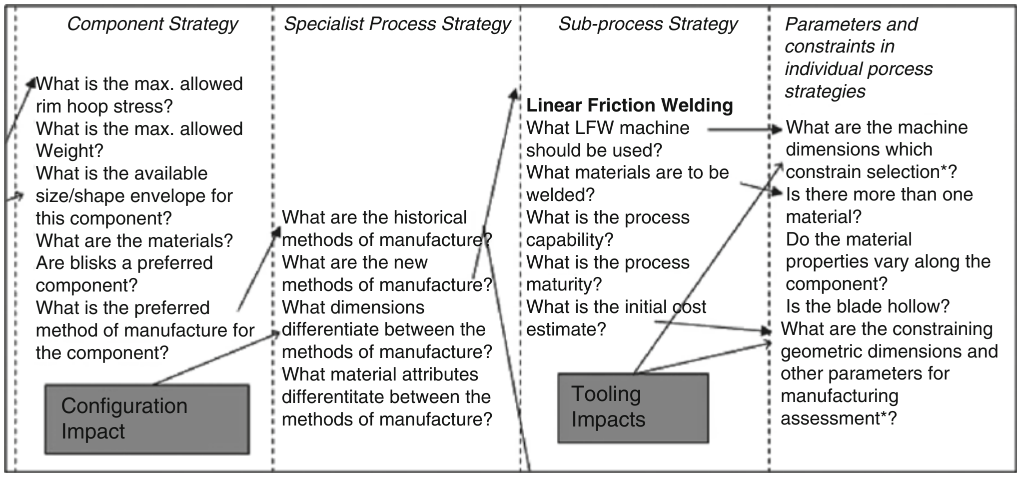

Fig. 4 Section of the schematic diagram

7 Potential Uses for the Schematic Diagram

The schematic diagram highlights all of the manufacturing knowledge requirements for preliminary design, not just those specific to one specialist domain. It would therefore give an engineer working in one particular area an appreciation of how their specific knowledge requirements fit into the overall analysis.

The diagram also gives a flexible approach to the acquisition of manufacturing knowledge by considering the interactions between the specialist domains. The knowledge would be acquired to complete the overall analysis but this would not be rigidly tied to a prescriptive design process.

Because the diagram deals with qualitative and quantitative knowledge, it enables the attributes associated with an innovative manufacturing process to be identified early during the preliminary design stage (in a qualitative form) and then quantified as the process is developed and the knowledge matures.

Once the knowledge is mature and standardised, the diagram could form the foundation for representing knowledge in a codified way, for example as an ontology or information model.

The next stage of research will focus on how to develop the schematic diagram into a knowledge system which can be used to identify, acquire and share innovative manufacturing knowledge for preliminary design. For the assessment of manufacturing processes in development during the preliminary design of complex mechanical components, this research highlighted the need to consider the maturity of the knowledge. It also demonstrated that in order to manage the risk in this knowledge successfully, it is necessary to account for the interaction of knowledge across the different specialist domains required in order to carry out a full manufacturing assessment. A suitable knowledge system therefore needs to consider the most appropriate methods for achieving this.

In order to facilitate the collection of explicit and tacit knowledge for innovative knowledge sharing, a combined community and commodity approach is proposed. The community approach should create an appropriate environment for tacit knowledge sharing. The commodity approach would support this, enabling the knowledge which is codifiable to be successfully captured and stored for reference during the project and for future projects.

The schematic diagram will form the foundation of the development of an operationalised methodology. This will be developed to enable the domain specialists necessary for achieving the design to identity, acquire and share the knowledge they require effectively. There will be two aspects to the methodology. Workshop sessions between specialists will be the main method of knowledge sharing. The knowledge identified which can be codified will then be recorded in an information system for future review and updating.

Currently the schematic diagram has been developed for an example component and two processes. It will need to be developed in order to become a tool which can be applied to a range of components and processes.

8 Conclusions

The case study confirmed the initial conceptual framework and demonstrated how it can be applied to a specific component. As expected, the manufacturing impact changed from being a configuration impact for initial manufacturing assessment to having a more specific impact when analysing the manufacturing sub-processes (manufacturing and tooling impacts). The knowledge therefore moves from abstract to specific as the manufacturing assessment progresses, with risks involved due to the maturity of the knowledge. The schematic diagram provides a means of identifying and assessing these risks and will be used to develop an operationalised methodology to identify, acquire and share innovative manufacturing knowledge during preliminary design.

9 Future Work

Having created a schematic diagram for a specific case of a component with two manufacturing processes, the next stage will be to create a general schematic diagram which could be used to acquire the knowledge for any component and process(es). This will then be used as a basis for creating an operationalised methodology within an organisation to identify, acquire and share manufacturing knowledge.

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A Unified Assembly Information Model for Design and Manufacturing

L. Qiao, F. Han, and A. Bernard

Abstract An obstacle in current digital design and manufacturing applications is that the information is hardly shared and exchanged among application systems. From the perspective of supporting assembly information integration throughout product design and manufacturing, a unified assembly information model and its modeling scheme are proposed. The modeling scheme includes a top-down modeling approach, a three dimensional framework describing the characteristics of the model, the model definition given in Unified Modeling Language (UML) and a 3D information expression method. A prototype implementation with CATIA CAD system is introduced to illustrate the application of the model in assembly design, design for assembly (DFA) analysis, process planning, assembly simulation and inspection.

Keywords Unified assembly information model · Top-down · Three dimensional framework

1 Introduction

The increasing complexity of product structure put forward new demands for product design and manufacturing performance. In digital product design and manufacturing environment, it is often cumbersome to realize the design and manufacturing integration as well as the whole product development process due to semantic heterogeneity between product definition descriptions and the relevant processes. Thus an importance issue is to establish a complete, unified and integrated digital assembly information model which forms a fully enabled process to support both product definition in product design and the rest of product lifecycle process definition. Typically the manufacturing process design so that an integrated digital design and manufacturing can be realized.

A unified assembly information model, taking product assembly activities as its foundation and 3D virtual product prototype as its carrier, specifies information content and criterion required in product assembly processes in design and process planning phases. It can be used to represent assembly design and manufacturing information, assembly design, design for assembly analysis, assembly process planning, assembly process simulation and assembly inspection process, replacing the traditional 2D engineering drawing with a 3D-based information model. The model can further support assembly related information in the entire product lifecycle processes and become the main basis for digital design and manufacturing.

At present, some widely accepted information modeling standards and specifications relevant to product design and manufacturing such as STEP, OAGIS and ISA95 have provided certain descriptions of product assembly information. But they are not able to provide the representation for the various information needed in product assembly design, process design, DFA analysis and neither they can support corresponding assembly simulation nor provide corresponding modeling schemes for assembly information. In recent years, some research methods related to the feature technology, modeling language and knowledge engineering have been introduced to the study of representation, organization and management of assembly information. Qiao et al. proposed a manufacturing process modeling method based on Process Specification Language to enhance the interoperability among different manufacturing application systems [1]. Product information was described as an assembly semantic model, and a virtual assembly planning system based on Pro/E environment was established [2]. Rachuri

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et al. addressed an object-oriented definition of an assembly model called Open Assembly Model (OAM), which defined both a system level conceptual model and associated hierarchical relationships for product assembly information [3]. Assembly features were captured for a product model of reference, describing information for handling components and connection information among components [4]. Ding et al. built lightweight representation and annotation attaching with 3D model for collaborative design representation [5]. Some researchers have also conducted research on standard data expression format for converting assembly model data between CAD systems and virtual assembly systems [6]. However, it is difficult to find adequate models that provide unified and complete descriptions of assembly information for digital design and manufacturing applications.

This paper presents a study of building a unified assembly information model with the consideration of consistent information representation and being supportive to the information integration relevant to assembly processes from design to manufacturing in product lifecycle applications. A scheme of building such a unified assembly information model and a three dimensional framework describing the diverse characteristics of the model have been proposed. The assembly model has been defined, which contains five categories assembly information at present, that is, assembly design information, assemblability evaluation information, assembly process information, assembly simulation information and assembly inspection information. In order to facilitate the use of the model, an effort has been made in explicit information expression in 3D environment. A prototype work of developing assembly information expression with CATIA is introduced in the paper.

2 Modeling Scheme and Characteristics of the Model

The purpose of building a unified assembly information model is to provide a uniform definition and specification of information related to assembly activities in the entire process: from design to manufacturing. The assembly information model, dependent on but can be much beyond the information of a common solid 3D product model, can be used to guide assembly design, assembly process design, assembly process simulation and assembly inspection, realizing the expression and transmission of assembly information as well as seamless integration among digital application systems. Furthermore, the use of the model may simplify the process of product design and manufacturing and truly realize 3D digital design and manufacturing, shortening the product development cycle. For all of the purposes a "Top-Down" approach to modelling the assembly information is utilized to detail the assembly information from design to manufacturing and from concept to implementation. A three dimensional framework is presented to show multi-view expression capability of the unified assembly information model.

2.1 The Top-Down Modeling Approach

In order to take into account the necessary assembly information to be used in product design and manufacturing, a Top-Down approach has been applied in building the unified assembly information model (Fig. 1). The approach allows gradual decomposition and refinement of the assembly information all the way through different processes. To begin with, conceptual design can be conducted according to the functional requirements of a product and the functional model of the product being built. Then the hierarchical structure of the product is designed by matching the structure with its functional decomposition, obtaining assembly motion information as well. In the detailed part design stage, the assembly connection information can also be obtained through constraint decomposition. A DFA process can be applied to obtain assemblability evaluation information of the product regarding economic and technological criteria. With DFA process, assembly information can be modified according to the DFA analysis results.

To make the unified assembly information model support assembly process design, assembly simulation optimization and assembly process detection simultaneously, the subassembly process design information model should convey the process design intent in more flexible and semantic ways such as views of various bill of materials (BOM), annotation of dimensions and tolerances, and technical notes in certain digital application environment using 3D solid models. Assembly sequence information and assembly path information in the unified assembly information model should carry the results of assembly process design.

Considering assembly tooling design, assembly process information such as assembly location, assembly supporting information and assembly clamping information should be referred. The assembly precision requirements of a product can be satisfied through a process of assembly process tolerance allocation, which uses assembly tolerance information to calculate the allocated tolerance result in different components. The unified assembly information model tends to support the dynamic simulation of assembly process, avoiding traditional experience errors. Meanwhile it supports simulation and analysis for key process parameters, assembly interference and ergonomic as well as optimizes assembly

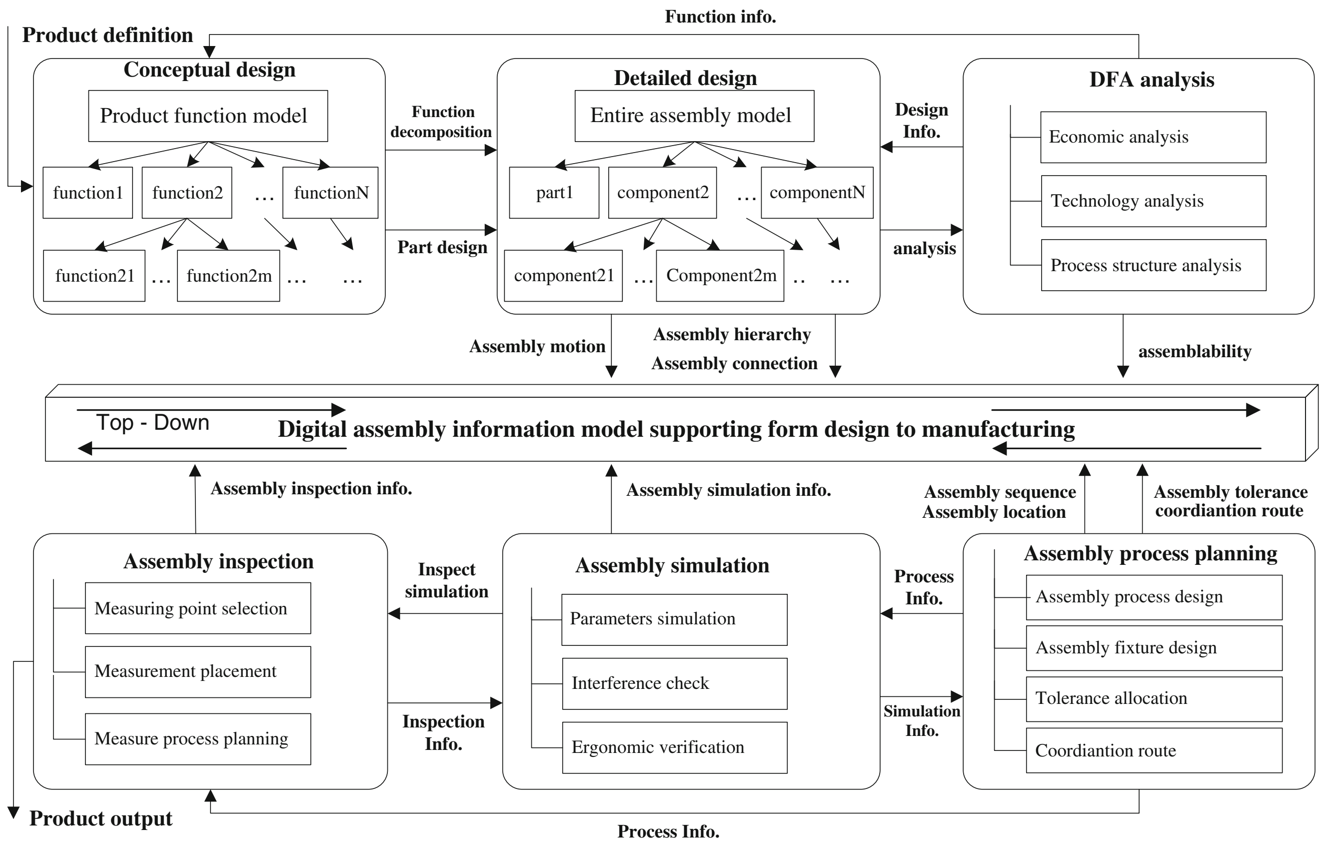

Fig. 1 Digital assembly information modeling method based on top-down

process through its assembly process simulation and analysis. The unified assembly information model should be able to compare the tooling 3D model inspected on-line with 3D model of the product, so that on-line assembly inspection can be achieved and the integration and sharing of the inspection data in all processes "from design to manufacturing" can be ensured by its analysis for measurement point definition, point layout and measurement planning.

In Top-Down modeling scheme, there are three major procedures of modeling the unified assembly information: stage decomposition of digital assembly information, establishment of the theme of information model function, and building the information model in detail following the steps of defining the model "from entity to relationship to attribute" and "from concept model to logic model then to physical model". The use of "Top-Down" modelling approach can not only get macro grasp of information model but also consider more comprehensively the detailed description of the model. In this way, complex assembly information in design and manufacturing is divided into a number of theme functional modules so as to facilitate the construction of the unified assembly information model, with more emphasis on the definition of the model in detail and ease of validation of the model built.

2.2 The Characteristic of the Model in a Three Dimensional Framework

The Top-Down approach of the unified assembly information modelling exhibits the stages of digital assembly process. It also, from coarse to fine, refines the assembly information model step by step with the proceeding of product design and manufacturing process. However, the unified assembly information model is a complex application model that describes actual problems. The complexity of application environments determines the model's multiple identities, perspectives and levels. In this study, a multi-dimensional framework of the unified assembly information model has been set forth to represent these characteristics. The framework analysis is addressed in the following by describing the functions of different sub-information models in the unified assembly information and their relationships, thus ensuring the model's adaptability and scalability.

The first characteristic of the model is the views of data that the model concerns and ultimately form the model dimensions. In the unified assembly information model, the product structure is the root of the expression of assembly information model and a key feature of the model.

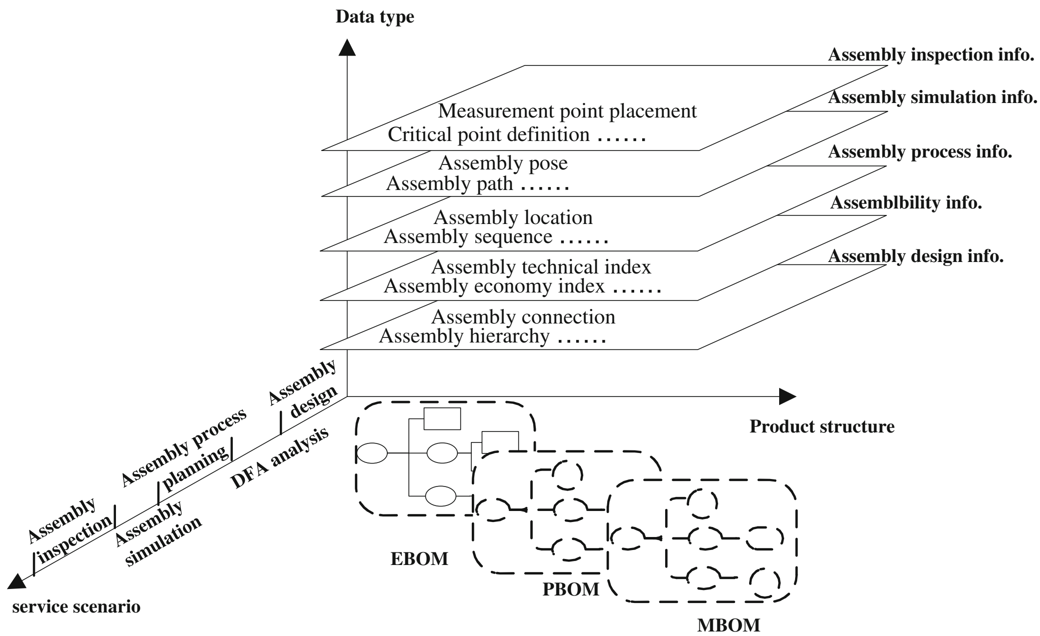

Fig. 2 The characteristic of unified assembly information model in a three dimensional framework

Meanwhile, the object of the assembly information model can describe a process that changes along with the product development process instead of keeping static itself all the time. In another words, the information object in the model evolutes with the development of assembly process and is closely related with the assembly process.

With this characteristic, the unified assembly model can link the lifecycle assembly information so as to support a serial assembly processes from design to manufacturing. The serial assembly processes are the different assembly phases in product development, such as assembly design, design for assembly evaluation, assembly process planning, and so on. The information contained in each phase can be categorized as views of assembly data type. A three dimensional framework has been defined to describe the characteristics of the unified assembly information model as shown in Fig. 2. One dimension describes the characteristic of multiple data types. The other two dimensions in the framework represent product structures and the service scenario respectively.

The relationship among a product and its parts and components are in the type of hierarchical structure relationship, and can be represented in the product structure dimension. The hierarchical relationship in the design stage is normally organized in the form of an engineering bill of materials (BOM). In assembly process design stage, process information is added and part structures of the engineering BOM are adjusted and rearranged accordingly. By validating the feasibility and quality of the assembly process plan generated via assembly simulation and analysis, assembly process plans and a manufacturing BOM can be created.

The service scenario dimension indicates that the unified assembly information model is defined with the ability of data services to the relevant processes from design to manufacturing: assembly design, DFA analysis, assembly process planning, assembly simulation, assembly inspection etc. This characterises the model to express information in an effective way and make the access and transmission of information easier, realizing a unified management of information carriers. To meet the requirement of data services of different assembly processes, a four-layer process-cored data structure is defined for the unified assembly information model data [7]. Figure 3 depicts the four layers: the process layer, data object layer, instance layer and definition layer. In the process layer, process descriptive ontology is introduced to describe the relationship among assembly activities such as sequence, parallel, substitution, etc. The configuration information in product structures and multi-processes can also be embodied in this structure. In the data object layer, in order to provide a serial of standard service operations like copying, pasting, deleting and so on to data objects, assembly related data entities are encapsulated corresponding to the process structure. The data instance items referred by the top process structure are described at the instance layer, including the relations between items and the relation properties. All the objects and documents which have nothing to do with the process and instance are included in the definition layer. Quotations and encapsulations are applied between layers. By refined definition of different information in the model, service interfaces and tools corresponding to processes are provided with convenience.

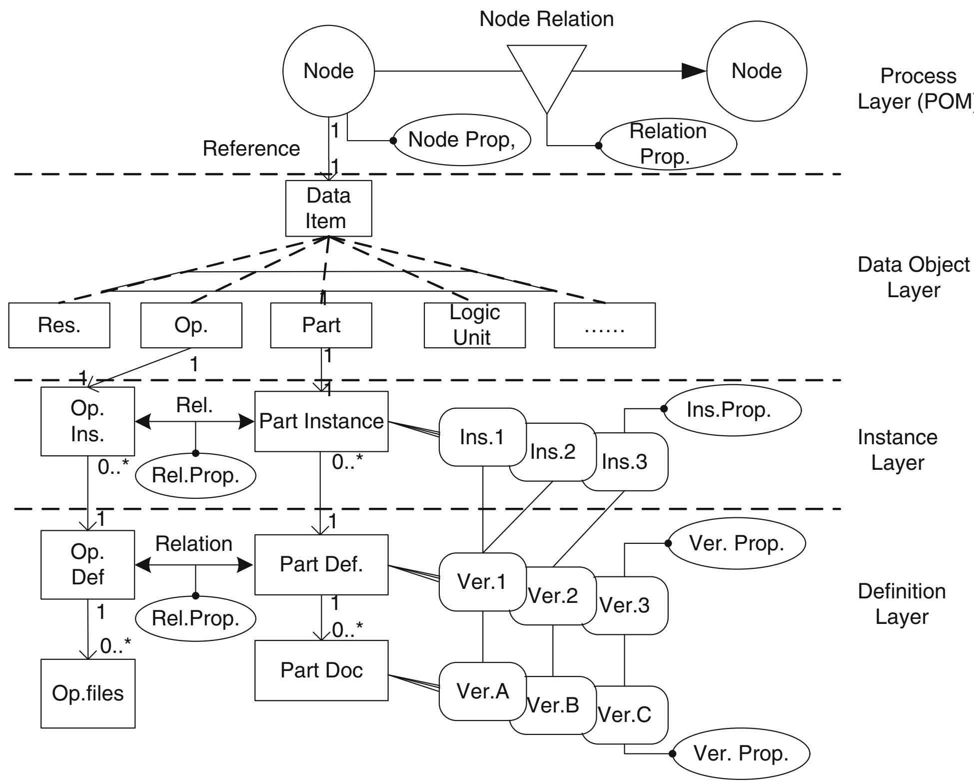

Fig. 3 The four-layer process-cored data structure of the model

3 The Model Definition

The modeling methods and the three dimensional framework of the unified assembly information model based on Top-Down describe the modeling frame of the unified assembly information model. The detailed specific contents of the unified assembly information model and the relationships between information on the basis of the frame description are established using the object-oriented UML as shown in Fig. 4.

Assembly design information is composed of fit, position relation, connection and kinematic information. The fit, which includes two categories, the geometric elements of fit characteristics and fit relation, is specifically used to describe the fit type and accuracy between parts and components of a product. Fit relation is expressed with the connection types of the geometric elements describing the fit characteristics, including clearance fit, interference fit and transition fit. Position relation is mainly used to describe the adjacency relationship between parts and components, namely the installation position between them. It can be divided into four basic types: orientation, alignment, attaching, and insertion relationship. The connection information expresses the definition of assembly connection feature as well as the adoption of the method of assembly connection. And the definition of assembly connection feature refers to the connection description need to be defined for the assembly connections in a product, such as the location points of a connecting hole and the direction of the connecting operation. Kinematic information is the motion constraint relations between the parts and components, such as the relative motion relationship.

In the unified assembly information model, the information needed in the integration of a DFA analysis process with CAD systems is defined. In order to certify and give re-engineering recommendations under the premise of the realization of functions, a DFA analysis module obtains information about assembly directly from a CAD system, and provides analysis as well as evaluation of the performance of product assembly. Two types of evaluations for the assembly can usually be generated, based on economical criteria and technological criteria. The unified assembly information model builds class to express the information on the economic indicators including assembly time, cost and efficiency, as well as the information on the technical indicators such as structured coefficient of the product or process, accessibility, and the efficiency factors of human (comfort, security) etc.

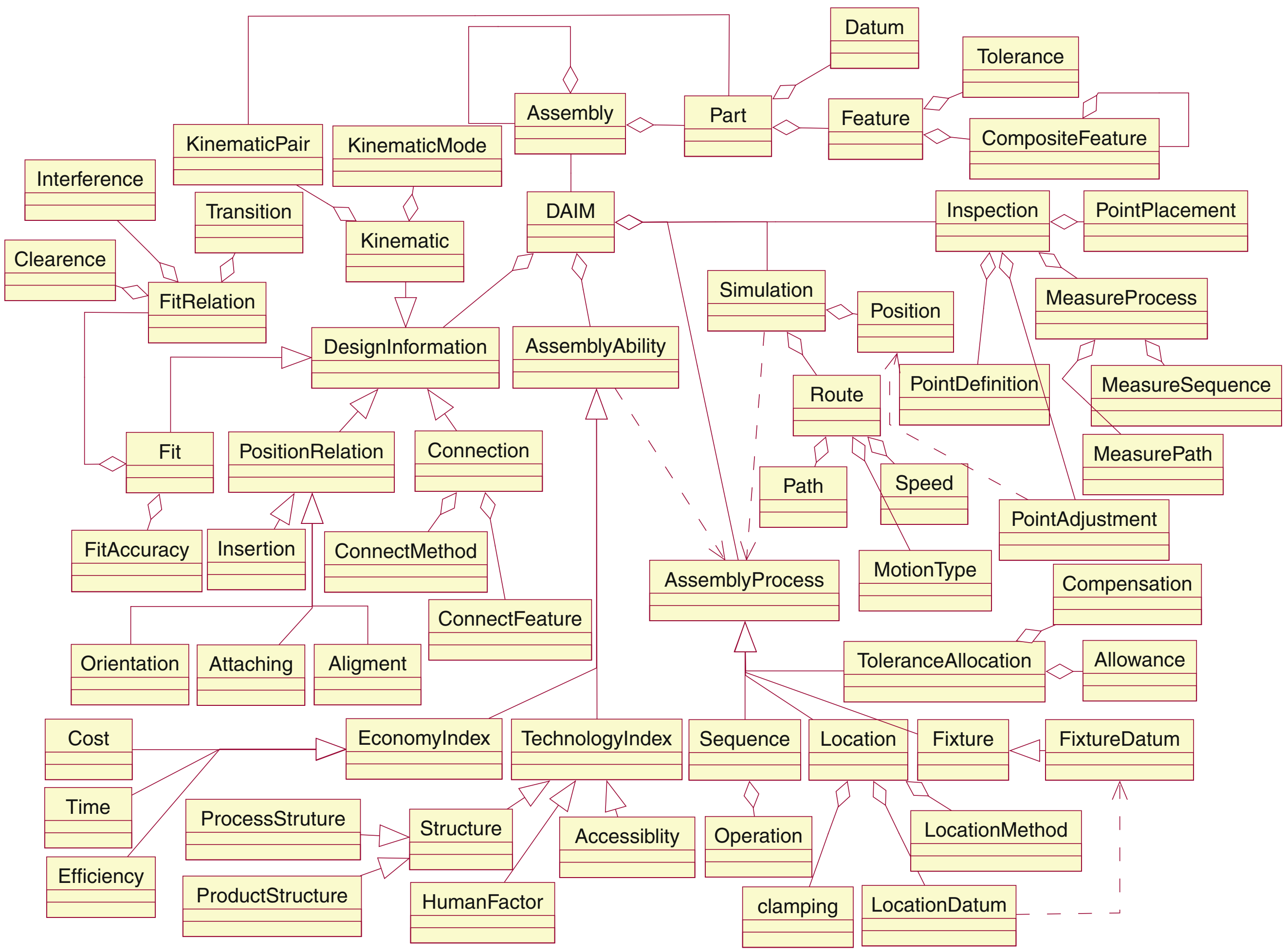

Fig. 4 The unified assembly information model in UML

Assembly process planning involves the following stages of activities: the process division, the assembly location design, the assembly sequencing and the process simulation. The assembly process information includes assembly sequence information, assembly location information, fixture design information and assembly tolerance allocation information. According to the identification of the process division surface, the structure of the components in a product will be divided into manufacturing cells which are relatively independent in structure and simpler in process. The information of assembly location and assembly clamping are the data basis of assembly fixture design. The allocation of assembly tolerance can refer to the assembly tolerance allocation information.

The unified assembly information model also contains the information of assembly environment and process in assembly simulation. It describes the essential entities that are necessary to create assembly simulations including simulation activities, analysis and optimization in 3D environment, prompting the correctness of the verification of assembly design and process design in the whole process from design to manufacturing. The assembly simulation information defined in this model includes: information on the analysis of DFA in the digital pre-assembly process, information on the analysis and the optimization of assembly process in the assembly process simulation, assembly path information, position and ergonomics coefficient generated in the assembly process simulation.

Assembly inspection information includes the definition and layout of measuring points with the key characteristics, measurement process information, and poses adjustment information. The best plan of assembly points can be determined according to the digital assembly inspection information. One can carry out the optimization calculation of the best assembly location for parts and components according to assembly process requirements, process tolerance and the measuring data of parts and components.

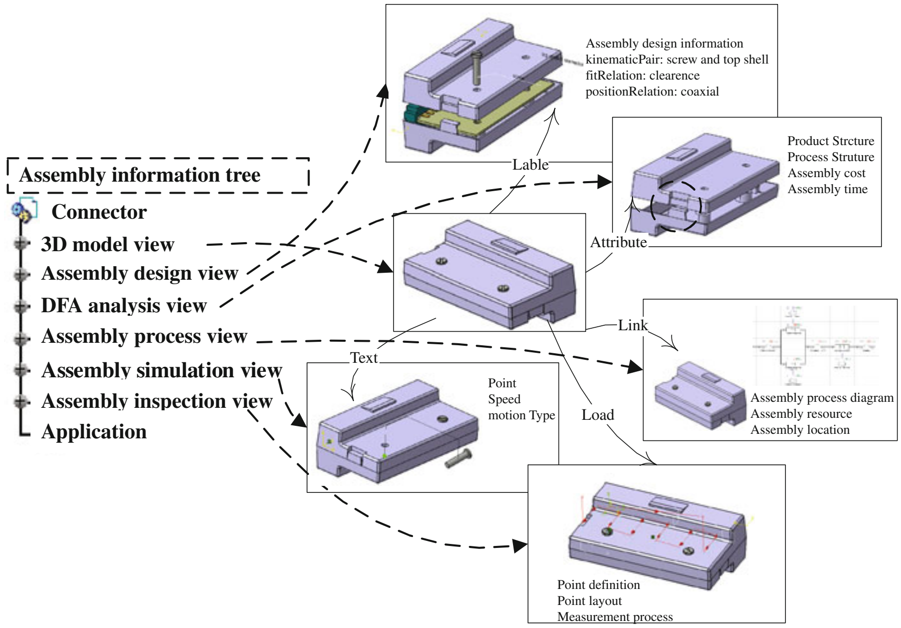

Fig. 5 Expression of unified assembly information model based on 3D model

4 Expression Assembly Information onto 3D Models

The unified assembly information model provides neutral definitions for information needed to develop the various software application systems related to assembly design and manufacturing. It plays an important role for the system developers who use the model as the basis of designing the interface and database of the system. However, with more and more active involvement of the end users of the application systems, such as product designers, process planners, shop-floor manufacturing engineers and service engineers, as well as the direct customers of the product to be produced, the information model should be represented explicitly for those people in cooperation with a 3D product model that can directly express product technical information so as to better serve the demand of data applications from design to manufacturing.

A prototype work expressing the assembly information model connected with 3D model has been conducted in this study. In order to express the unified assembly information by text and by graph, a combination of multi-tables and multi-views has been adopted. Taking the initial 3D product model as a shared model, the content of the assembly information is added to the 3D model, including annotations, comments, texts, links, attributes etc. Multiple views are defined to express different aspects of the unified assembly information and are controlled by the mechanism of view display. In the shared mode, there is complete information to show the design intent. When assembly manufacturing process data is generated, it can be added to the 3D model as well, rather than using 2D drawings. A data organization mechanism is built to support the expression of the assembly information affiliated to 3D models. In the mechanism, information is well managed by feature tree, PPR (product, process and resource) tree, table relationships and view association respectively.

An implementation of the above information expression in 3D model has been carried out with CATIA system. Based on the secondary development in CATIA using the scripting language VBScript, assembly information can be defined and attached via the 3D model of the product in different stages of product development. Figure 5 shows an example component – a connector and its assembly information in different processes. Views are created and managed. Different views are associated with different assembly activities in order to accept and provide the required information. The Figure indicates the views and the main data representing information in assembly design, DFA analysis, assembly process, assembly simulation and assembly inspection.

5 Conclusions

A unified assembly information model has been presented. This model and the three dimensional framework of the model provide a feasibility of representing all relevant assembly information throughout product assembly design and manufacturing. It supports the integration and coordination of the assembly information among various stages of assembly activities in product development. By affiliating the assembly information onto 3D product models, this work can facilitate the addition, utilization and transformation of the multiple-stage product design and manufacturing information. With this way of modelling, the definition of product data, its preservation and transmission has been completely changed. Furthermore, efforts on detailing the information model and its application in assembly applications are undergone by the authors.

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Ontological Semantics of Standards and PLM Repositories in the Product Development Phase

M. Franke, P. Klein, L. Schröder, and K.-D. Thoben

Abstract In order to optimally exploit the large amounts of engineering information stored in contemporary PLM systems, the concept of knowledge based engineering (KBE) can be considered from a PLM perspective. By eventually combining product structures and implicit semantics provided by PLM-systems on the one hand, and domain-specific standards on the other hand we believe to have identified a key enabler for KBE. As an initial step we describe a coupling of a CAD system with a semantic representation of engineering knowledge using formal ontologies. By application of automatic reasoning, engineering knowledge gained from the product structure and domain-specific standards allows us to reduce time-consuming manual work in classifying overlaps between parts in a CAD model as intentional overlaps (e.g. with gaskets) or design failures.

Keywords PLM · KBE · Semantics · Ontology · Reasoner

1 Introduction

Today, business competitiveness is usually broken down into success factors such as decreased time-to-market, higher success rates in product introduction, reduced project failure rates, minimized manufacturing costs, increased product and process innovation, and improved communication among departments and business partners. This obviously impacts the requirements on classical business applications like ERP (Enterprise Resource Planning), PLM, or CAx software, and consequently affects the corresponding research activities [1].

Even the performance of the initial product development phase is affected not only by technological challenges but also by the socio-technical context in which it happens. A scenario of a globally distributed development team may serve to illustrate this. In this scenario, networked enterprise systems or PLM-systems, respectively, become the main backbone for coordinating geographically dispersed engineering activities [2].

In fact, collaborative features have become standard in contemporary PLM systems, such as ENOVIA [3], providing a single front-end to multiple information sources, enabling dispersed data storage, real time visualisation of the emerging product, global change management, or design-in-context approaches.

Nevertheless, as pointed out by Bermell-Garcia and Fan [2] one practical question is still not solved sufficiently: "How to retain and capitalise the large amount of engineering information stored in PLM repositories as intellectual property assets?" [2]

This leads to the field of knowledge based engineering and in detail to research covering KBE services within PLM [4, 2, 5]: Keeping in mind that PLM-systems provide a key technology that enables generic and cost-effective sharing of product and process information across a wide range of software systems (not only CAx) and across organizational barriers, several researchers have raised the idea of implementing standardised PLM interfaces as a possible solution for interoperability between two different KBE-systems [4]. As one of the results the "KBE Services for PLM" RFP was published in September 2005 by OMG [6].

However, as we discuss later, standardisation in general is not only a possible solution for such an interoperability issue. In combination with specific PDM/PLM information, standards can play an important role in covering one of the most critical KBE issues: knowledge acquisition.

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2 Background

The high impact of product-related decisions in the initial development phase on the overall product costs and lead time is as well-known as the coexistence of a pronounced lack of product-related knowledge in this phase.

While some current research approaches try to decrease lead-time by shifting the identification and solving of engineering problems to the early phase of the product development process (so called *front loading*) [7], others are addressing solutions to ramp up the initial creative phases by specific supporting tools (*inventive design*). The approach of knowledge based engineering directly focuses on the reduction of lead-time and costs by supporting and in particular automating repetitive design tasks [8].

Our own qualitative experience in the area of knowledge management gained in research projects in collaboration with several industry branches (aircraft, maritime, automotive) indicates that such tasks represent most of the work in the product development process. According to, e.g., a quantitative analysis by Skarka [8], a proportion of about 80% of the overall design tasks is routine and consists of repetitive tasks such as adaptation of existing parts to slight changes in the overall geometry, or checking for clashes and omissions.

The enormous potential of a successfully implemented KBE solution has been already validated by several research projects [9–11]. By each of those implementations, a notable time reduction from several days to a few hours for the respective design tasks has been achieved, while in parallel a constant quality due to the repeatability can be ensured.

However, this is by no means a general justification for an unlimited deployment of a KBE system. A usage of KBE technologies may not be effective in different situations, e.g. if a problem is simple enough to solve it in a less technology-centered way (i.e. without KBE technologies) or if it is not possible to extract or to codifiy the required knowledge, e.g. in the absence of a clearly defined design process [8].

2.1 Different Approaches to Knowledge Based Engineering

As already pointed out by Penoyer [12], knowledge based engineering appears, at first glance, to be a tautology – usually every person (and especially every engineer) involved in a product development process will define her engineering tasks as based on specific knowledge.

Hence for our purposes, knowledge based engineering (KBE) will be defined in close conjunction with KBE systems. Within a KBE system, design knowledge is represented in a formal manner and enables the system to automate specific design tasks mostly unique to the company's product development experience.

Each KBE system provides on the one hand an interface to capture the knowledge in terms of logical rules, algorithms, or constraints, and on the other hand an output module to trigger adjacent CAx systems or/and visualise results [13].

In this sense, knowledge based engineering can be seen as the process of gathering, managing, and using engineering knowledge to automate the design process by usage of a KBE system [14]. In this context, the meaning of *automate* even covers analysis tasks in terms of validation or quality checking, since the interpretation of the output of CAx tools, such as CATIA's DMU Space Analysis, requires engineering knowledge about the mechanical parts involved.

An emerging trend in the field of knowledge based engineering is to set up a background ontology, link one or more of the available CAx engineering tools to it, and thus provide context specific engineering knowledge for different tasks covered by separate CAx tools [11]. Other research addresses the idea of using the ontology in order to represent a generative model and thus enabling design automation [8].

Surprisingly, one of the most noticeable advantages of such an approach seems to be not yet fully exhausted by the solutions developed so far: the ability of using formal logic and automated reasoning in order to generate further findings and reports for control and steering purposes.

A further advantage of the usage of ontologies appears in the context of the upcoming requirement for PLM systems to capture and manage the technical decisions made by product developers in the initial development phase. Such a decision-tracking is of increasing importance in the context of product warranties on the one hand, and as a valuable input for follow-up product developments on the other hand.

The standard approach to retaining product design related knowledge and experience is to produce and store documents such as lessons-learned or best-practices.

Consequently, the respective expert defines the terminology, verbalisation, and level of detail of the represented knowledge by herself. In the long run, this way of archival storage implies a continuous decrease of comprehensibility, since terminology and wording may change over time. The transfer of knowledge into an ontology expressed in a description logic with a formally grounded semantics avoids such a semantic dilution and thus ensures that the codified knowledge is sustainable, in particular remains readable, maintainable, and convertible over time.

2.2 The Challenge of Knowledge Acquisition

The requirement of capturing domain specific knowledge can be seen as one of the main challenges in the field of Knowledge Based Engineering [15].

Even if several methodologies (e.g. MOKA [16]) have been elaborated to guide knowledge acquisition activities and thus avoid omitting essential knowledge [8], they usually require a time-consuming collection and analysis of (often implicit) knowledge about the product and its design process, respectively [17]. Thus, most approaches to designing KBE-Tools address especially repetitive engineering tasks [18, 10], since the potential to reduce time and cost by means of such approaches has to be balanced against the effort needed to gather and formalize the required knowledge in a scheme (e.g. an ontology) [18].

Contemporary CAD systems provide several enhancements to support product data management features, and thus very often constitute the main link to a global PLM-system within an enterprise IT infrastructure. These modules allow not only storing and managing a broad range of product-related non-geometrical data, but give the user a visual and intuitive access via the graphical representation of a product and its product structure, respectively [19]. Thus, capturing PDM-data via context specific dialogs within the respective CAD-systems has become common practice.

Based upon these coupling concepts, the use of a CAD user interface for a KBE system is an obvious and already implemented idea. In fact, many of the leading CAD applications provide add-on modules for KBE related features. The *knowledge advisor*, *knowledge expert* and *product knowledge template* modules of the CAD application CATIA can serve as examples. Based on a parameterized CAD model, they provide functions like formulas (to create dependencies between parameters), rules (such as If... then...) and power copys (user defined features, allowing to partly reuse design procedures) [20]. Nevertheless, integrated methods for an easy knowledge acquisition remain a key hurdle for the application of these functions [8].

2.3 PLM and Standards – An Underestimated Source for Knowledge Acquisition

For PLM systems, *product structures* have become one of the most important backbones to which the various types of metadata are attached. Within PLM applications, the requirements of taxonomical *naming* and *numbering* lead to sophisticated algorithms that cope with the complexity of providing a distinct, non-redundant namespace [21]. In parallel to such internal representation logic, several formal standards are used in the area of PLM in order to represent the product and its product structure appropriately.

In the area of mechanical engineering, standardisation is usually not only a clustered set of generic product information, or a taxonomy of a specific domain, but it comprises a high amount of codified knowledge, in terms of, e.g., calculation rules, engineering constraints, schemes for data exchange etc. The use of standards to cover such codified knowledge is based on a long history in the field of mechanical engineering, ranging from the VDI 2230 guideline that treats the systematic calculation of high duty bolted joints [22] up to the ISO 10303 standard for the computer-interpretable representation and exchange of product manufacturing information. Several specific KBE solutions cover the idea of using such codified knowledge for a specific design problem – a good example is given by [23], which implements the Italian VSR/PED rules for the verification of pressure vessels.

By a combination of both types of knowledge – product structures and namespaces provided by PLM systems, and existing domain specific standards – we believe to have identified a key stepping stone to harnessing knowledge acquisition in a principled and sustainable way.

As an initial proof of concept for the benefits that can be achieved using this type of combination, we describe below a semantic analysis of clashes and overlaps in CAD files. Our prototype of an analysis tool (called OntoDMU) is able to check semantically if an overlapping is a design failure or an intended feature, at least in those cases where standard parts are involved.

Specifically, we exploit that when a standard part is used in a product, the respective standardisation identifier remains available, usually as a section of the item name in the CAD model. For example in CATIA V5, when a nut is chosen from the standard part catalogue of the application, an expression such as ***ISO 4034*** *NUT M14 STEEL GRADE C HEXAGON HEAD NONPREFERRED* will be provided as a default part name in the product structure. This enables us to connect the relevant standard (in this case, ISO 4034) with a background ontology, which in turn helps us interpret the output of the analysis tool.

3 Practical Benefits Drafted in a Sample Scenario

Validating the correctness (the so-called quality) of a CAD model by analysing its compliance to corresponding engineering knowledge can be seen as a typical job for a designer. In this context, contemporary CAD files provide her with several support modules, e.g. for validating a mock-up against assembly requests, or checking its conformance with the PLM namespaces. One of those tasks is an investigation of the CAD-model in order to distinguish between intended part overlaps and overlaps to be attributed to design failures.

Looking specifically at the case of overlaps, it is by no means the case that every overlap is actually a design error – e.g. overlaps are often intentional in the case of bolts, whose threads are typically not modelled in the CAD software, so that a bolt will overlap with its nut. Similarly, deformations of gaskets (e.g. O-rings) are typically ignored (both for computational reasons and because one wishes to have the undeformed shape of the gasket in the design, e.g. for purposes of exploded views) so that they overlap with adjacent parts, even if sizes are appropriate. In fact, overlaps are actually mandatory in both examples, but do of course represent design errors in other cases, some of them subtly different – e.g. a bolt should not overlap with the parts it connects unless the latter also have threads.

Picking up the above mentioned gasket example Fig. 1 shows a half section view of the 3D-CAD-model of two flanges screwed together (e.g. used in context of pipe coupling).

The small circle represents a gasket. The parts in the background represent a bolt and a nut – screwed together. By using a half-section view of the assembled parts, a mechanical designer can check the correctness of the design and the CAD-model respectively (position, dimensions, overlapping etc). Thus, not only the gasket's position in the flange notch becomes visible, but also its intersection with the flange.

Being aware that a gasket normally consists of deformable Flouride rubber (FPM) the mechanical designer can easily identify the correctness of the overlap and the assembly as a whole, since no overlap would lead to a leaky assembly. Unfortunately, CAD-models can become confusing for complex products. To check overlaps of a gas-tanker assembly-model, for instance, leads to thousands of gasket intersections.

Using an interference detection module such as CATIA's DMU Space Analysis will provide the mechanical designer with a complete list of all overlaps, but the tool cannot distinguish between required overlaps and unintentional clashes. This is caused by the fact that no inferences are possible from a geometrical representation of a part to the part itself (for example: In a CAD application there is absolutely no difference between a geometrical model of a ring and a geometrical model of a gasket).

Figure 2 is a screenshot of the DMU Space Analysis report belonging to the CAD-model shown in Fig. 1. Even if it is a quite simple product and only identified overlappings are displayed, the list gets quite long and leads to time-consuming manual work.

By using the OntoDMU tool for the ontological analysis of the output of the DMU analyser as described in the present work, however, the designer can analyze this list of overlaps semantically and identify those overlaps that are not allowed.

As shown in Fig. 3, the OntoDMU prototype transforms the output of the DMU Space Analysis module into a set of individuals set against a background ontology, thus making it available for semantic analys using state-of-the-art automated reasoning. Next, we proceed to describe details of this method.

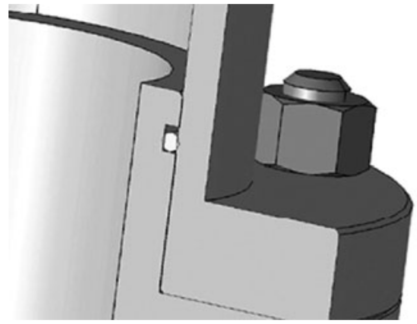

Fig. 1 Half-section view of the assembled flange

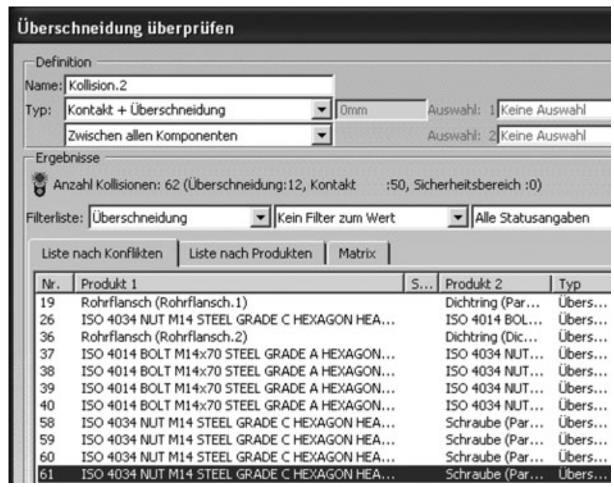

Fig. 2 Space analysis report – screenshot

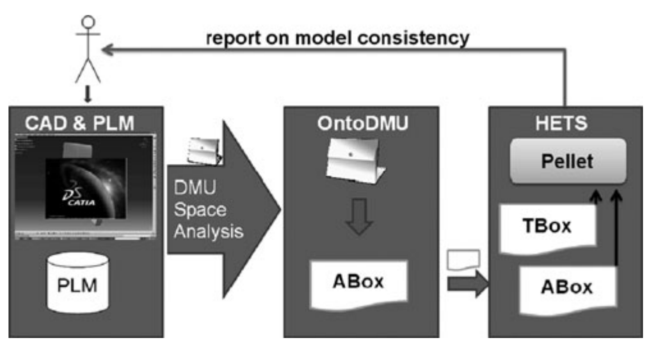

Fig. 3 architecture of the initial prototype

4 Approach

To capture the semantics of standards and PLM repositories, we propose to make use of formal ontologies expressed in a formal ontology language at the level of so-called description logics; specifically, we use the standard ontology language OWL-DL (Web Ontology Language), a W3C recommendation [24]. Description logics are tuned to offer an optimal degree of expressive power while retaining efficient decidability, and indeed come with high-performance optimized reasoners such as Pellet [25]. For purposes of describing engineering designs, this means that our background ontology is able to describe simple relationships between parts and components, such as existence, parthood, cardinality etc., but not the geometry or topology of a model. However, it turns out that a surprisingly large amount of knowledge can be captured in such a simple framework, and exploited for the automated consistency checking of CAD models. In t his process, it is precisely the simplicity of the language that allows us to use efficient reasoning and thus achieve a practically feasible semantic framework, which in the end even does offer support for geometry-related issues, such as overlapping, on a suitable level of abstraction. We emphasize that a representation in a formal logic carries a number of advantages over a hard-wired representation in software, in particular

- increased clarity of the representation
- independence of accidental features of the software environment
- reduced likelihood of errors, due to simplicity of expression and absence of side-effects
- improved interoperability.

It turns out that in order to reduce the complexity of modelling and keep an optimal level of modularity, it is useful to maintain two types of ontologies: An ambient ontology that covers abstract engineering knowledge, such as that rubber is deformable (and therefore rubber parts may overlap with adjacent parts since the deformation is usually not explicitly modelled) and, embedded therein, an ontology of standard (or enterprise standard) parts which represents and classifies a part catalogue against the ambient ontology, but typically does not otherwise encode any background knowledge. One benefit of this approach is that both parts of the ontology become much easier to maintain, and in particular the ontology of standard parts can mostly be generated automatically from part databases in the CAD system.

4.1 Using a Background Ontology

As discussed above, an ontology expressed in a formal description logic allows one to formally represent and store domain specific knowledge. It enables in particular a perspective where we regard a CAD model as a collection of instances of generic objects that we can view against the backdrop of the ontology. The ontology then serves as a template for maintaining consistency during the development of a product or the creation of variants. Moreover, the designer can further develop the ontology in order to make domain knowledge assumptions explicit and facilitate reuse of his designs.

We briefly recall some of the basic concepts of OWL to facilitate the understanding of the examples given further below. An OWL *class* represents a collection of objects; e.g. the class “bolt” stands for the collection of all individual bolts. Similarly, a *property* represents a relationship between objects, such as parthood. From the basic classes, one forms *concepts* by applying Boolean operators as known from propositional logic (conjunction, disjunction, negation) and so-called *restrictions* which govern the way in which an object is expected to be related to other objects. E.g. an existential restriction on the property “hasFeature”, qualified by the class “thread”, designates all objects that have some feature that is a thread. Similarly, a universal restriction on the property “hasPart”, qualified by the class “standardPart”, designates objects composed only of standard parts.

An ontological knowledge base then consists of two parts offering different perspectives on the domain: The structural information of a domain is characterized through its TBox (the *terminology*). The TBox consists of a set of inclusions between concepts, and as such allows expressing general knowledge such as “every bolt has a thread”, or “every car has four wheels and a colour”. Contrastingly, the ABox (the *assertions*) contains knowledge about individuals, say a particular car or a given occurrence of a standard part in a CAD model. It can state either that a given named individual (say, “myCar”) belongs to a given concept (e.g. that myCar is, in fact, a car) or that two individuals are related by a given property (e.g. that myCar is owned by me).

By default, an ontology has no restriction for naming. For this reason, the same element can have different labels in two or more ontologies (precisely because OWL does not implement the so-called unique-name assumption), but would not be detected as the same in case of merging the ontologies. Therefore, it is desirable that the label of each element is kept unique. If an element has a unique name in the real world, a designer can achieve such a unique labelling by using the same name within the ontology, following an appropriate transformation of name spaces. Additionally, an encapsulation into name spaces can be used to ensure unique labelling of items.

As already indicated, using an ontology as part of a KBE solution can improve the engineering processes, but at the same time, the modelling of an ontology can become very complex, especially if a generic approach is envisaged.

In the scenario described above, we focus on the standard part catalogue of CATIA V5 R16. This version comprises about 8838 standard parts, and each part has its specific properties and restrictions, which have to be implemented in the ontology (Fig. 4). For this reason, one of the main challenges is to reduce the effort and the complexity of modelling. In

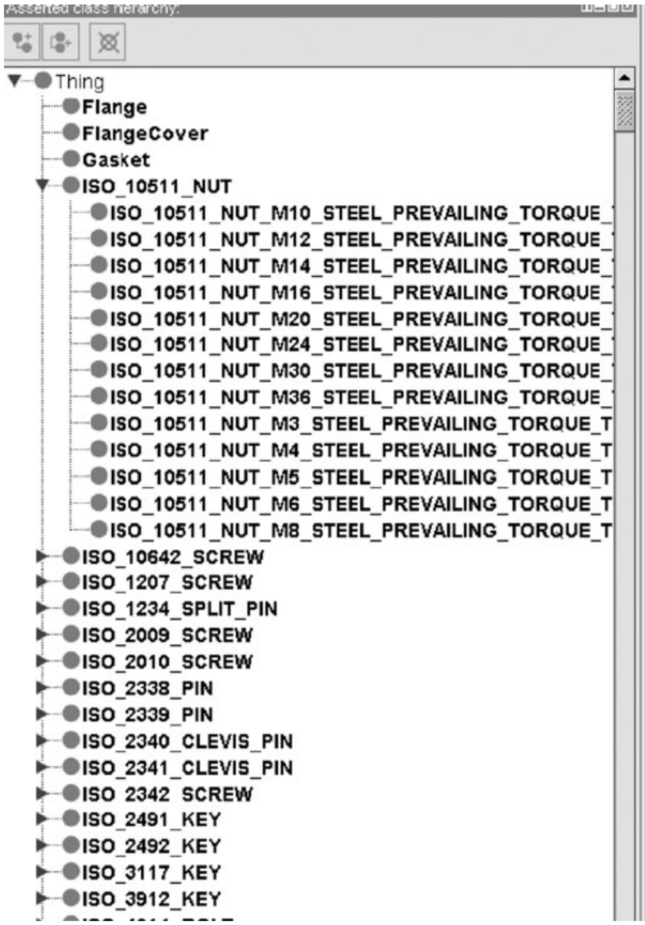

Fig. 4 Detail of the background ontology – screenshot

order to avoid such time consuming manual work, we have foreseen a special function in OntoDMU to import standard parts into concepts of the ontology (refer to Sect. 4.4).

The overall approach to determining the consistency of a CAD model with respect to the ontology is, then, as follows. The background ontology together with the ontology of standard parts exported from CATIA V5 formally constitutes a TBox. A second function of our OntoDMU tool is able to convert the output of CAD tools such as the DMU analyser into an OWL ABox over this TBox; then, the consistency check amounts to checking the consistency of the combined knowledge base. As discussed below, the technical framework that integrates all these tasks is the Bremen heterogeneous tool set Hets.

4.2 Ontology Languages

We digress briefly to discuss our choice of ontology language, limiting ourselves to the three main sublanguages of OWL: OWL Lite, OWL DL and OWL Full [24].

OWL Full features the highest expressivity; however, it does not currently have efficient reasoning support, and the logical complexity of the language makes it unlikely that such support will be developed in the foreseeable future. Since our approach to consistency checking of CAD models relies crucially on fully automated reasoning, OWL Full is, thus, not a suitable option. As mentioned above, efficient reasoners do exist for the sublanguages OWL Lite and OWL DL [26]. The complexity of OWL Lite is markedly below that of OWL, so that more efficient reasoning is possible for ontologies limiting themselves to the expressive means of OWL Lite (and efficiency remains an issue in our framework, as both the output of the DMU analyser and the imported ontology of standard parts tend to become large rather quickly). However, the expressive power of OWL Lite turns out to be too limited for our purposes; in particular, OWL Lite excludes conjunction and universal restriction, which we need to say things like "bolts have threads *and* intersect only with nuts" or "all members of the concept ***ISO 4034*** *NUT M14 STEEL* have an identical diameter of 14 mm".

Technically, OWL-DL ontologies can be written and stored in several ASCII-based formats. These formats can be translated into each other. Some reasoners, such Pellet, have corresponding translation functions. For using OWL-DL within Hets, it is necessary to generate the ontology in OWL Manchester Syntax [27]. Such a file can be opened with all common OWL readers, such as Protégé in version 4.

4.3 The Bremen Heterogeneous Tool Set

We embed our background ontology as well as our interface tool into the Bremen heterogeneous tool set (Hets) [28] which allows for the integrated use of a wide variety of logics and associated analysis and reasoning tools in a common framework, accessed via a graphical interface and connected by a network of logic translations. Relevant for purposes of the present work are the support offered in Hets for ontology languages including in particular OWL-DL Manchester Syntax and, as a more expressive correspondence language, first order logic, as well as the facilities provided in the Hets implementation framework for the easy integration of further logics.

The latter has allowed us to cast the output format of the DMU Analyzer as a very simple-minded logic, thus enabling integration of the OWL translation tool into the Hets framework and thereby, e.g., direct reasoning support for the combination of the tool output and the OWL background ontology in Pellet [25]. Figure 5 shows a screenshot of the Hets graphical interface and an interface window for a call to the Pellet reasoner.

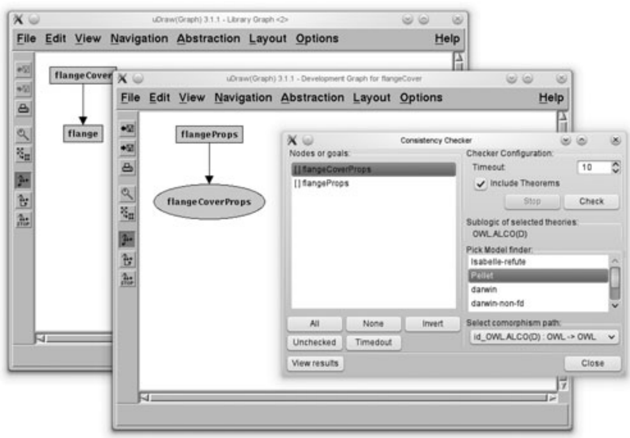

Fig. 5 Hets graphical interface (screenshot)

4.4 Semi-automatic Generation of Ontologies

The tool OntoDMU generates the ABox automatically and the background ontology semi-automatically. In the following, we describe these generation processes in more detail.

The background ontology should define all concepts a user needs for his own modelling purposes. In our concept, this includes standard parts (taken from the standard part catalogue of CATIA V5) as well as non-standard parts. Since non-standard parts are user or enterprise specific, the idea of importing non-standard parts is a priori a non-trivial proposition. We intend to implement an interface in order to transfer the product-structures and namespaces from PDM/PLM into the background ontology.

The standard parts, on the other hand, are stored in a separate catalogue-folder managed by CATIA. Hence OntoDMU can access the respective information without starting CATIA, and every change in the catalogue folder can be easily updated in the ontology. OntoDMU extracts all relevant information from the files automatically and transfers it into the ontology. A part from the standard catalogue is transformed into a concept, and its properties are inserted as a combination of data and object properties.

For example, the class of nuts ***ISO 4034*** *NUT M14 STEEL GRADE C HEXAGON HEAD NONPREFERRED* is such a catalogue part. Its name directly contains information about its properties. In this example, the material and the diameter of the nut can be read off from the name, and inserted as explicit properties of the item. Further information gained from the part name is the relevant standard (in this case, ISO 4034), which induces further properties by relations with the background ontology. In our case the respective information is: *every ISO 4034 part is a nut and as such has an inner thread.* In detail, this information arises as follows: we record in the ontology of standard parts that every ISO 4043 part is a nut, and we have captured, in the background ontology, the piece of general engineering knowledge stating that every nut has an inner thread.

As examples of "non-standard" parts (i.e. not from the CATIA V5 catalogue), to be though of as enterprise standard, the ontology of our scenario includes classes *Flange*, *Gasket* and *FlangeCover*, which are currently maintained manually.

General knowledge about parts as such is then integrated with knowledge relating to the topic covered by our target geometric analysis tool, overlaps or, in the terminology used in the tool output, *interferences*, between parts. As discussed later, interferences may either be intentional or indicate design failures. The knowledge used in classifying interferences accordingly is modelled using properties of a dedicated class "interference"; details are given further below.

4.5 Structural Information in the Background Ontology

The standard parts share a common interface of object properties. At present, OntoDMU can identify *type*, *material, diameter* and *length* as object properties, and extract these properties from standard part names.

The above-mentioned class *interference* represents an overlap relation between parts, possibly annotated with further data generated by the geometric analysis tool. The analysis tool generates instances of this class in an XML representation format, which the OntoDMU tool automatically converts into an ABox describing a collection of individuals inhabiting the class *Interference,* with additional data describing the participating parts and their classification according to the part ontology.

The classification of interferences as intended or faulty is now cast as a consistency check of the ABox thus generated with the background ontology, which must hence contain a formalization of rules stating what types of overlaps between parts are allowed, forbidden, or, in fact, mandatory. To see why these cases even arise, consider the following examples:

- Two bolts should never overlap; such and overlap, if detected, will always be classified as a design failure.
- A gasket, being deformable, may overlap with other parts. These, however, should be of a suitable type – e.g. a gasket should not overlap with a bolt, but may overlap with a flange
- Bolts in fact *must* always overlap with some other part (unless threads are explicitly modelled), namely with a part (typically a nut) having an inner thread, whose type and diameter match that of the bolt. These, however, are the *only* overlaps allowed for bolts.

It is an important design decision to which classes these pieces of knowledge should be attached in the background ontology. To balance the conflicting design goals of modularity, human readability, and efficiency of reasoning, we adopt the following approach. We attach general pieces of knowledge such as "bolts should always (and only) overlap with parts that have inner threads" to the class *Interference* as a list of alternative exceptions.

Contrastingly, more specific information, such as that the part that a bolt overlaps with should have matching thread type and diameter, is attached to the relevant class of bolts, or more precisely to the relevant type of thread. E.g. the class representing the thread type M12 states that any part having an outer thread of this type may overlap only with parts having an inner thread of type M12.

Unfortunately, even for small part ontologies this leads to long and hard-to-parse lists of restrictions (Fig. 6); we thus to some degree sacrifice human readability in favour of ease of machine processing: an alternative approach is to attach restrictions entirely to part classes instead of to the class *interference*. This leads to better modularity and is easier to read for humans. However, this requires an increased use of so-called inverse properties which traverse object properties *backwards* (in this case, from a part participating in a particular interference to the interference itself), which leads to increased processing time. In our experiments using Pellet, this meant an increase from about 1 min 40 s in the analysis of a particular CAD model to more than 15 min.

Currently, restrictions relating standard and non-standard parts in the ontology are created manually. Our envisaged approach foresees to extract those relations from a PLM repository. A precondition for this extraction is to have annotated product structure items in the PLM/PDM system.

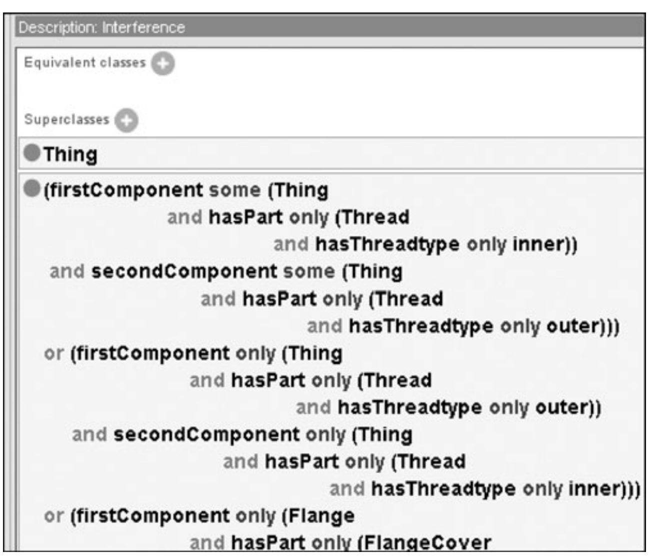

Fig. 6 Additional restrictions on the concept *interference*

Those annotations include a unique reference between a part and its concept.

5 A Remark on Using Default Logic

As discussed above, the *interference* concept captures most of the explicit allowed interferences. The effort for such an explicit interference modelling increases quadratically with the number of implemented concepts. An interesting point to be made is that for purposes of the specification of the background ontology, it would be useful to have a language with defaults available; see Chap. 6 of [29] for a brief explanation of defaults and an overview of existing approaches to adding them to ontology languages. Defaults are not currently included as a feature in OWL, which we continue to use nonetheless for sake of its well-developed reasoning support. We outline briefly how defaults could be employed to increase in particular the degree of modularity of the background ontology.

Roughly speaking, default implications state that given certain conditions, certain conclusions are expected to hold *normally*, but may be overridden when more specific information about the given situation becomes available. The standard example is that birds *normally* fly, thus leading us to conclude provisionally (*defeasibly*) that a particular bird flies unless more specific information about it becomes available, such as that the given bird is a penguin. In the concrete setting of specifying legal and illegal overlaps of parts in a CAD object, having such a mechanism available would simplify the overall structure of the ontology rather strongly: To begin, one would be able to just say that generally, parts should not overlap. This general proviso would then be overridden by exceptions, such as that gaskets typically overlap with other specific parts having dedicated channels for the gasket; the latter could, again, be overridden in particular cases where the channel might be absent. This approach is *modular* because one can extend the range of available parts without having to adapt the general principles (e.g. we never have to adapt our initial default stating that parts do not overlap, even though exceptions to this keep accumulating).

Consequently, an OWL modelling of the situation has to circumvent this lack of expressivity rather visibly. E.g. all exceptions to the general rule that parts do not overlap are currently explicitly attached to the concept of an interference as shown above.

6 Conclusion

The fact that most current KBE solutions address only individual design problems and do not offer enterprise-level solutions largely goes back to problems of knowledge acquisition. Even though this level is typically covered by PLM systems and hence established information repositories do exist, there is to date no automated way for transforming this information into codified knowledge as it is typically used in knowledge based engineering rules.

To contribute to realising the vision of a sustainable capitalisation of the engineering information stored in PLM repositories as intellectual property assets, we have presented an approach to combining product structures and namespaces provided by PLM-systems on the one hand and significant domain specific standards on the other hand in order to establish a background ontology and thus create a powerful semantic representation of codified engineering knowledge.

Even though the current implementation of our OntoDMU tool, which translates the output of a standard geometric analysis tool into a knowledge representation format that allows for a connection to a background ontology of codified engineering knowledge, is still at the prototype stage, benefits to be gained by its usage already become clearly visible. The productive interplay between a practical design problem, which reappears in different design contexts, and the background ontology created as part of the framework, leads to a clear reduction of manual intervention in the validation of CAD objects.

The approach of having an ambient ontology of general engineering knowledge in parallel with an ontology of standard parts which is automatically generated from CAD part catalogues and PLM systems is promising and will be further elaborated. As a next step, an annotated product structure will be used in conjunction with the background ontology, thus allowing for semi-automatic generation and maintenance of ontologies also of non-standard parts.

At the same time, the work presented here constitutes an important prerequisite for ontological support in the actual core PLM processes: the semantically correct integration of data fed back to the manufacturer from the product during its life cycle requires a semanticized representation of design objects as facilitated by our ontological approach to CAD. Future steps in our research program include the implementation of a semantical underpinning of sensor data and other Middle-of-Life data to obtain intelligent decision support for the full product life cycle, thus enabling optimal feedback of PLM data into the design and development process. As demonstrated in the CAD case study presented here, we expect substantial added value from the use of fully automated ontological reasoning in modern DL engines (as opposed to a classical programming approach as pursued, e.g. in the ICAD system [30]) with respect to decision quality as well as extensibility and adaptability; here, the use of a standard ontology language such as OWL carries the promise of a high degree of both interoperability and sustainability. The approach via a core set of ontologies managed independently of the involved software tools both reduces the overall maintenance effort and enables an increased degree of knowledge reuse, with knowledge being made available to the entire range of CAx systems involved in the product life cycle.

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Knowledge Management Applications for Creative and Inventive Design in Global Product Development

Computerised Range of Products in the Automotive Supply Industry

J. Feldhusen, A. Nagarajah, and S. Schubert

Abstract This chapter describes an approach to optimize the design process of adaptable products. Therefore self organizing map (SOM) is applied to support the developer. SOM is able to assess the similarity of requirement lists. Assuming that similar requirement lists lead to similar products, the SOM is able to identify the existing product, which has to be changed least to fulfill a new order. For applying SOM, the requirement lists have to be prepared in multiple steps. The requirements have to be structured, transferred into unambiguous language and they have to be quantified. In this chapter a focus is put on the quantification of the requirements.

Keywords Adaptable products · Engineering design · Self organizing map · Range of products

1 Introduction

In today's automotive supply industry, enterprises are forced to reduce the development costs. To achieve this aim, a majority of the products are developed by adapting or varying already existing products. This kind of product development is named here as adaptable product development [1].

What is today's approach for an adaptable product development in these enterprises? The aim of the designers is to minimize the changes of existing product and therefore to reduce the cost and time for the subsequent processes like manufacturing or assembling. Thus, for a new development order, the designers take the previous solution as the development base and adapt it to fulfill the new request. An important prerequisite for this approach is that the changes of the requirements, compared to the product variant used as the development base, have to be identified. Hereby, components of the base product variant, which have to be changed, are recognized [2].

From many projects in the automotive industry it can be concluded that last product version is not always the suitable one to be used as a development base. The reason for selecting the last product version is that the knowledge is not documented in a way, which is feasible to work with. For the documentation the product requirements should be associated with the product characteristics clearly. Such an allocation cannot be carried out, because not all of the product characteristics are defined by the designer explicitly. In this case an expert system, which supports him to identify the implicit allocation, would help. A rule-based system has little prospect of success, because these systems usually assume that information is available explicitly [3]. In this chapter the data mining method "self organizing map" (SOM) is introduced for solving the problem. Data mining means extracting implicit, yet unknown information, from raw data [4]. Therefore the computer based system has to be enabled to search automatically after regularities and patterns in data and to carry out abstraction to get the structures of the implicit assignment as the result.

An important prerequisite for the application of data mining methods is that there exists a sufficient data base. Therefore these methods can only be used partially for a new product development. But for an adaptable product development the data from previous versions of the product can be used. It is assumed that the amount and type of the requirements in the supplier industry remains constant and only the expression (values) changes. Hence there is enough data to use SOM for adaptable product development.

Furthermore for the handling of the requirements in a SOM based system it is essential to subdivide the requirements into elementary-textual components and to quantify them, i.e. to describe them with an unequivocal numerical value for representing in computer. For a new development order, which is given mainly by a change of requirement values, the SOM is able to identify the existing product version with the most potential to fulfill the new order.

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2 The Approach Of The Research Project

For a successful procedure of this research, it is necessary to divide the main goal into the following sub goals:

1. The first aim is to define the requirements from the specifications of the original equipment manufacturers (OEM) in textual elementary components and to quantify them in order to prepare them applicable for SOM.
2. The second aim is the development of a SOM that supports the developer in a meaningful way with the accomplishment of the adaptable product development for a new order, which should be suitable for the intended requirements.

2.1 Procedure for the Creation of Basic Requirement Components

In this project, specifications of different OEMs for bonnet locking systems (Fig. 1) have been analyzed. First all requirements have been extracted in original phrase and listed in a table. Specifications of bonnet locking systems contain a high number of requirements. In order to determine missing requirements a structuring would be reasonable. Therefore classes are found. The number of requirements per class is smaller and therefore missing requirements are easier to detect. Further the classification supports the engineer like a checklist not to miss a whole domain of requirements. The handling of the whole requirement list is also simplified.

A further step in the preparation process is the linguistic standardization. The German Automotive Association (VDA) provides a guideline which aims for a precise communication between OEM and supplier. Included in this guideline, recommendations for the setting up of the requirement list is included. According to this recommendation the requirements are transferred into unambiguous and clear textual components [5]. The user uses defined components to describe the requirements. In addition there is a "weak word-list" containing words not to be used. The requirement in direct quotation of the specification is e.g. "In case of a front impact, the bonnet must not be opened unintentionally." Transformed according to the VDA standard the requirement will be "For a front impact (condition) the locking system (subject) have to (demand-word) keep the bonnet (object) closed (keep . . . closed = action)."

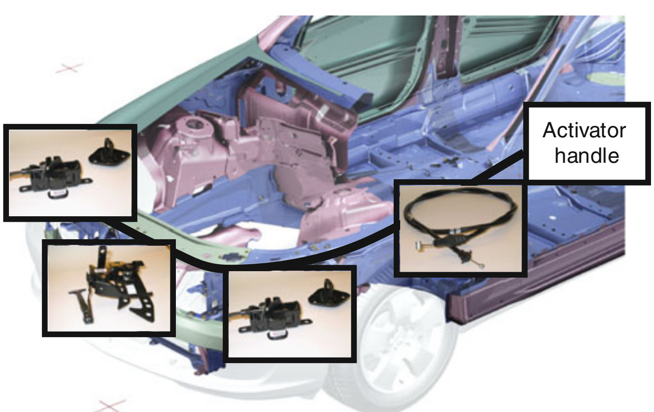

Fig. 1 Bonnet locking system

2.2 Procedure to Quantify Requirements

Basically requirements can be distinguished into qualitative and quantitative requirements. For quantification and therewith for preparation for SOM, it is reasonable not just to distinguish between qualitative and quantitative requirements, but to refine these groups [6] (Fig. 2). Generally qualitative requirements are not processable for SOM, but they can be prepared to be processable. The need for a preparation of quantitative requirements is depending on the type of the quantitative requirement.

Quantitative requirements can either contain a numerical value (type 1) or a word (type 2), which defines the attribute precisely. An accepted tolerance or minimum force is normally expressed by a numerical value; a material is normally expressed by a word. The quantitative requirements described with a numerical value, can be directly processed by SOM. To process the verbally described quantitative requirements, the attribute has to be transferred into a numerical value, e.g. aluminium is set to "1", while stainless steel is "12". The associated number has to have no meaningful connection to the material. A definition table is set up and the assigned number is transferred into the requirement list (Fig. 3). Thus the SOM is able to determine whether the materials of two requirement lists are identical.

There is existing one further group of quantitative requirements (type 3), containing requirements which refer to general documents like standards, guidelines or laws, e.g. "The bonnet locking system has to meet conditions according to a certain standard A". For SOM it is just important that product related to a certain requirement list fulfills this standard A, while the exact conditions of the standard A can be neglected. For a requirement like this, it is sufficient just to store a Boolean value. "1" if the requirement, in this case the fulfillment of the Standard A, is considered, "0" if the requirement is not mentioned in the requirement list.

There are also three different types of qualitative requirements. The first group is referring to the companies internal knowledge like a previous variant of the product (type 4),

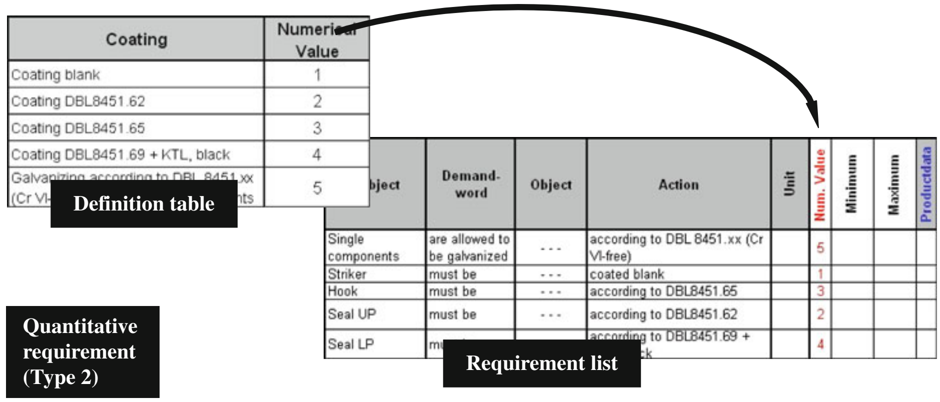

Fig. 2 Assignment of numerical values to requirements (type 2)

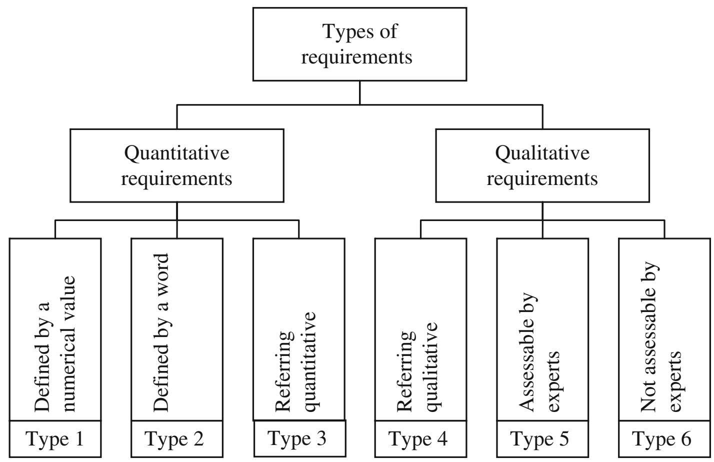

Fig. 3 Types of requirements

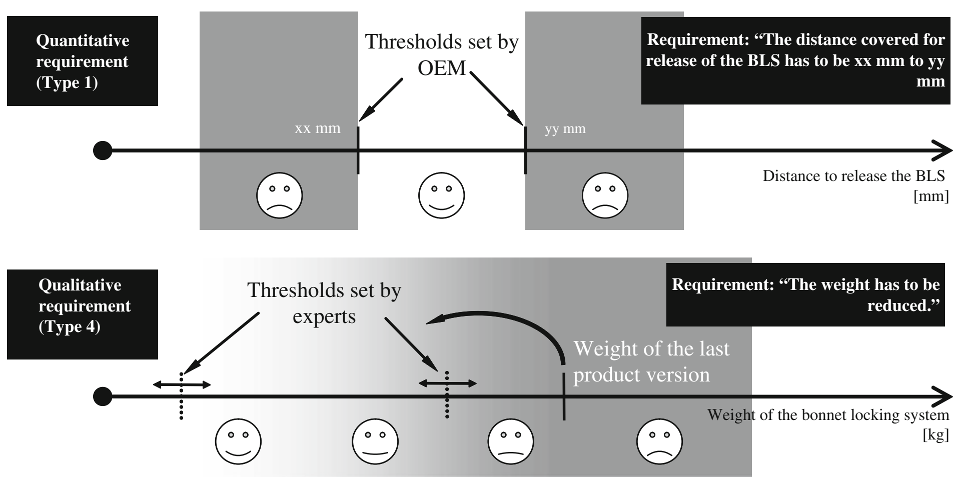

Fig. 4 Assignment of numerical values to qualitative requirements (type 4)

e.g. "The weight has to be reduced compared to the previous variant". To interpret this requirement domain-specific knowledge is necessary. No exact numerical value can be determined for this type of requirements. Therefore a workshop with experts is executed. Experts are able to determine a range which is reasonable for a certain requirement. The thresholds of the range provide numerical values, which can be processed by SOM, but compared to the thresholds of a quantitative requirement they are not fixed (Fig. 4).

The last two subgroups of qualitative requirements are also domain-specific, but not referring to any object. In both subgroups the requirements are phrased generally. The requirements belonging to the first subgroup (type 5) can be assessed by experts, e.g. "The sound level of the bonnet locking system during the closure has to be low." These requirements are also transferred into numerical values during the mentioned workshop.

For the remaining requirements, which constitute the last subgroup, an assessment by experts is not reasonable.

A requirement demanding failsafe can not be concretized by a numerical value (type 6). So the information, if a requirement of this subgroup is contained or disregarded in a requirement list is stored by a Boolean value, “1” if it is considered, otherwise “0”.

3 SOM Basics

SOM is a special data-mining-method, which is used to identify and furthermore to visualize complex numerical coherences.

The generic term “data-mining” includes a great number of so called “knowledge-generating” methods. These methods are mainly used to detect complex coherences in data, mainly in those cases where common statistical tools will not generate satisfying solutions [4].

Based on historical data of a product, for example, real reasons for quality-defects of that product can be detected, even though these causes are hidden in the data [4].

Several powerful methods and algorithms were developed, each with specific capabilities (random-forest, support-vector-machines, neural networks, etc.) [7]. The correct use of these and other methods will finally result in an expert-system which can be used for classification, approximation and prediction [4].

The SOM is a special architecture of artificial neural networks. Neural networks are information processing structures, which have been built up with the knowledge of the function of the human brain. They consist of a large number of highly interconnected elements, called neurons. Between the neurons, there are connection weights, which are established through the learning process. Through the adjustment of connection weights, such a network is able to in to recognize structures and to generalize them. Basically there are two kind of learning methods: supervised and non-supervised. In a supervised learning method a training record including the desired results is given. The network has to learn the relationship. For a non-supervised learning there is no desired output. Networks with this learning method are used for clustering. SOM belongs to the non-supervised learning systems. This makes them suitable for the mapping of the requirements.

3.1 Realisation of SOM for Adoptable Product Development

An essential feature of a SOM is to map the similarity structure of a high-dimensional data space on a two dimensional chart [8]. This is an appropriate measure to reduce the evaluation effort by using a simple type of visualization, which can easily be analyzed.

The first step of the mapping process is to extract data vectors from complex requirement lists as shown in Fig. 5, in which the standardized requirements are listed. In order to get a consistent dataset, all requirement lists have to contain the same set of requirements, so the requirement vectors contain the same number and kind of elements. Thus, each variant of the already existing requirement lists is transformed into a standardized requirement vector.

3.2 Training

Next, a non-supervised learning procedure is carried out: A batch of the requirement vectors is applied to SOM.

In this case the “batch algorithm” is used, as a significantly faster computation of the SOM is performed in comparison to the incremental-learning SOM algorithm [9].

The algorithm works in the following way: All Units of the grid are initialized with a model vector. Randomly a variant vector is picked out of the dataset and the distance between each model vector of the grid and the variant vector is calculated. The unit with the shortest distance to the variant vector is called best matching unit (bmu) and this variant vector will be placed on the map at this location. This operation is repeated while all variant vectors are picked out of the data set and are placed on the map. Thereafter the model vectors are adapted. Due to the inclusion of all already placed vectors at every mapping-iteration for a new variant vector, the similarity structure will be trained on a higher degree (Fig. 6).

To achieve a high reliability of the SOM, it has to be trained with a large number of requirement lists, whereas a sufficient number of requirement lists is higher than the number of requirements. In case the number of available requirement lists is not adequate, the spectrum of requirements also has to be decreased. Currently, research is carried out to clarify if the application of modules and therefore a lower number of required training sets on SOM is sufficient. At this point of time a main problem is the non-consideration of the interactions between these modules. A measure to compensate this limitation has to be elaborated.

After the training process the SOM grid has a topology, consisting of nodes. In each node a requirement vector is stored, similar ones close to each other, different ones are located having a distance in between.

Beside the actual requirements the requirement vectors contain also an expert based rating value specifying the suitability of the requirement list to describe the already existing products. A value close to “1” stands for a high suitability, “0” for no suitability.

								Req. List 1				Req. List 2			
Requirement Identificationnumber	Condition	Subject	Demand-word	Object	Action	Weighting	Unit	Num. Value	Minimum	Maximum	Productdata	Num. Value	Minimum	Maximum	Productdata
44	In the unlocked condition	Striker	must	opening height	have		mm		aa	bb			cc	dd	
45	---	Seal UP	must	according to	be coated			2				3			
46	---	The BLS	must	Standard No.123 (OEM)	meet the conditions according			0				1			
47	---	The BLS	must	the previous product version	be lighter than		kg		ee	ff			gg	hh	
48	---	The BLS	ought	---	to be disassembled quickly		s		ii	jj			kk	ll	
67	---	The acitvator handle	has	---	to be user-friendly			1				1			

Fig. 5 Standardized requirement lists

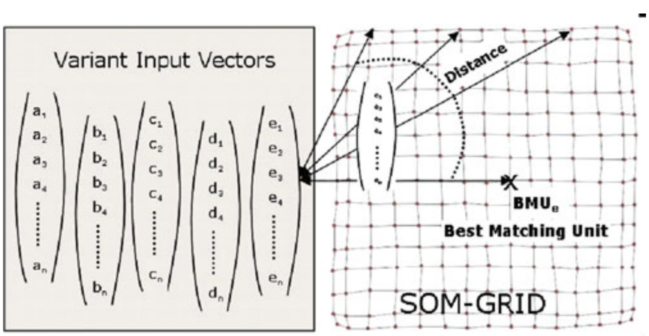

Fig. 6 Training process

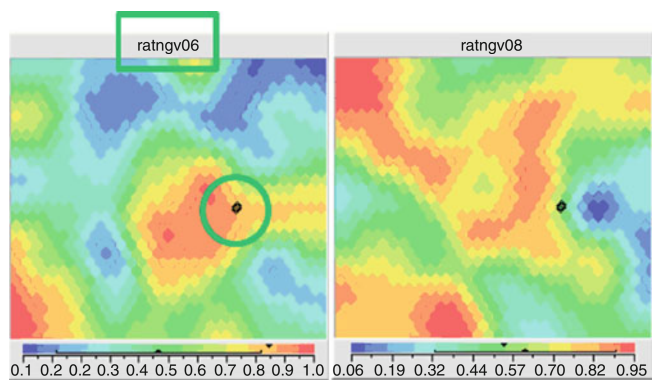

Fig. 7 Fitness landscapes of existing requirement lists "06" and "08"

3.3 Determination of Most Suitable Development Base

In case a new requirement list is provided by the OEM, this new requirement list is transformed into a requirement vector. This new requirement vector is compared with all vectors in the SOM grid, whereas the new vector has no ratings. Thus, in the comparison the requirements are neglected. The comb containing the most similar requirement vector to the new vector is highlighted. This comparison is done by calculating the Euclidian distance.

Thus the rating of all vectors in the SOM grid for one particular existing solution can be interrogated. For a better visualization of the interrogation, the map is dyed with a colour scheme. In Fig. 7 the ratings for two different existing solutions are shown. By comparing the ratings of the new requirement vector for all existing solutions, the existing solution rated highest can be chosen as the most appropriate development base. In Fig. 7 the rating of the existing solution number 6 is higher than the rating of solution number 8, so the more appropriate development base would the existing solution number 6.

In addition, the graphical representation as a landscape has the advantage that the stability of the selected solution can be assessed. In case of two products assessed with a similar matching value, the stability can be a further criterion for the selection of a product. By examination of the area around the black comb, it can be assessed how stable the product variant is against further modifications: A comb in a large area indexing a high compliance seems to be more robust towards further modifications. Thus the selection of a variant with a high stability is more applicable.

4 Summary

The aim of this research project is to apply a SOM based system to shorten the time for conceptual design of an adaptable product development. Therefore an SOM-based system can be applied on requirement lists of existing products to identify solutions that are suitable as a development base for a new product order. The engineer is able to select one of these proposed solutions as a development base. This can be adapted with a minimal effort for the new product order. This increases the customer satisfaction, because the new product is based on an approved product.

To apply specifications provided by OEMs to SOM, the requirements have to be extracted and edited. This process has several steps. In this chapter an emphasis is put on the quantification of the requirements. First the requirements are distinguished into six different types, which are all either quantitative or qualitative. In this context a description by an exact word is also considered as quantitative. Examples are the assignment of a material or a standard, which has to be fulfilled. In case of a description by word the quantitative requirements need a preparation. Furthermore all qualitative requirements need to be prepared. Examples are shown for each type.

Currently the quantification of different types of requirements is made in workshops by experts. This is time-consuming and expensive. In future the aim is to use fuzzy-sets. Therefore the requirements have to be prepared further. The requirement demanding "the bonnet locking system to be user-friendly" is easily assessable for experts. For a fuzzy-set this requirement will be split into elementary requirements, e.g. defining a maximum hand-force needed and optimal shape of the grip.

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Case-Based Reasoning for Adaptive Aluminum Extrusion Die Design Together with Parameters by Neural Networks

S. Butdee and S. Tichkiewitch

Abstract Nowadays Aluminum extrusion die design is a critical task for improving productivity which involves with quality, time and cost. Case-Based Reasoning (CBR) method has been successfully applied to support the die design process in order to design a new die by tackling previous problems together with their solutions to match with a new similar problem. Such solutions are selected and modified to solve the present problem. However, the applications of the CBR are useful only retrieving previous features whereas the critical parameters are missing. In additions, the experience learning to such parameters are limited. This chapter proposes Artificial Neural Network (ANN) to associate the CBR in order to learning previous parameters and predict to the new die design according to the primitive die modification. The most satisfactory is to accommodate the optimal parameters of extrusion processes.

Keywords Adaptive die design and parameters · Optimal aluminum extrusion · Case-based reasoning · Neural networks

1 Introduction

Aluminum extrusion is a hot deformation process used to produce long, straight, semi finished metal products such as bars, solid and hollow sections, tubes and many shapes of products. The hot aluminum extrusion process is pressed under high pressure and temperature in a specific machine. A billet is squeezed from close container to be pushed through a die to reduce its section [1]. A profile shape is deformed in order to be adapted to the die orifice shape on an aluminum extrusion press. The main tooling of aluminum extrusion process is a die which is performed aluminum profile shapes. The die design is a critical task for improving productivity which involves with quality, time and cost. Case-Based Reasoning (CBR) method has been successfully applied to support the die design process in order to design a new die by tackling previous problems together with their solutions to match with a new similar problem. Such solutions are selected and modified to solve the present problem. However, the applications of the CBR are useful only retrieving previous features whereas the critical parameters are missing. In additions, the experience learning to such parameters are limited. This chapter proposes Artificial Neural Network (ANN) to associate the CBR in order to learning previous parameters and predict to the new die design according to the primitive die modification. Artificial neural network methodology applied to solve the complex or specific problem in engineering works [2]. The case study of an example die design is discussed.

2 Aluminium Extrusion Die Design

Die design is one of crucial task in aluminum extrusion process. The success and failure cases are studied and analyzed in order to use their information from these cases for improving a new die design to avoid failure case. In practice, a die may be tested many times before the extrusion profile is satisfactory. If the extruded profile shape is not perfect, die geometry will be modified such as bearing length to balance extrusion speed of the section for obtaining good quality profile shape. The quality factors include a less number of testing, long life of the die, high productivity and so on. In general, die design process consists of selection of a die type and size, calculation profile section shrinkage, determination hot aluminum flow controlling, determination of die orifice dimension and deflection of tongue, calculation of the

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bearing lengths, supporting tool design. Each die design process should be focused on the parameters that have effect to die efficiency such as shape factor, extrude ability, extrusion ratio, etc. In fact, die design or die geometry will be modified following the profile characteristics, especially, profile shapes and dimensions. In term of efficient operators, they should have a thorough understanding of the different functions of each die features (i.e. leg, sink in, porthole, bearing etc.). These features will be modified to interact with the process parameters and each of the product characteristics. The complex flow of material in the extrusion die or container often creates different deformation conditions in various regions of an extruded product. Die design has to imagine the metal flow pattern in die and container in order to make decisions for the definition of each die feature. Especially, die orifice and bearing length are the important features, which have directly affected with metal flow velocity. In theory, flow velocity of each point on the section should be balanced to avoid the extruded profile twist.

The die design is based on skills and experiences from a die designer, who accumulates the knowledge of die design for using this knowledge to solve the die design problems. Decision making for designing he die consists of selection of the suitable press, selection of type of die and its materials, laying out the profile(s) on the die in order to optimize the extrusion yield, handling with unbalance velocity of the metal flow on each point of the sections, the consolidation of the tooling to withstand in extrusion process, etc. CAD is used to associate a designer to improve productivity not only be able to reduce time but also can ensure a quality of die design. Feature based technique is one of the most popular used to support the CBR method in the phase of rapid modification.

3 Feature Based Library

Traditionally, CAD tooling offered for three methods; Solid modeling, Wire-frame modeling and Surface modeling. Solid modeling is one of the effective modeling which is the most similar object to the real part [3]. However, the solid model is still needed to develop in the aspects of fast design respond and design based on the previous parts or features. Therefore, the feature based technology was emerged [4]. The principles of feature can be several characteristics. They are form features, function features, tolerance features, assembly features, material features and property features. The original concept of feature base is derived variant approach of process planning which is believed that the similar parts are should have the similar process plans. The variant approach contains four steps. First is collected the existing process plans and stored in the library. Second, the stored plans are classified, coded and indicated. Third, the new part is input and matched to the system library with the same or similar parts. The matched parts are retrieved and shown. The information is shown which are not only the parts, but also their process plans. Fourth, one or many of the shown process plans are selected and modified to fit with the new part. This concept can save a lot of time and can be applied to many fields of industrial manufacturing; design, planning, production, etc. Feature-based design tools have been applied to many applications. Thomson [5] stated the applications of the feature concept to reverse engineering to machine maintenance. The paper explained that the method of using CMM in order to get machine part features and then recorded them in the library. Gayreti and Abdalla [6] expressed a feature based prototype system for the evaluation and optimization of manufacturing processes. A feature is defined as generic shape carrying product information, which aid design or communication between design and manufacturing.

Die geometry can be classified into three categories. They are solid, hollow and semi-hollow die. The difference die geometries provide the various shapes of the end product profiles. Figure 1 shows the example of feature based extrusion die which is recorded in the case library. The die assembly (AC245/1) composes of three components. They are feeder plate (FPAC245-01), die plate (DPAC245-01), and back plate (BKAC245-01). Each component has their own feature class, whereas some of them shares with the common class. For example, the open pocket, The close pocket, the edge chamfer feature class can share with the three components. By constant, the tap hole is specifically used for the feeder plate feature class. The class benefits to manage on the process planning method selection. The feature based die library has advantages when they are stored with a well-structured

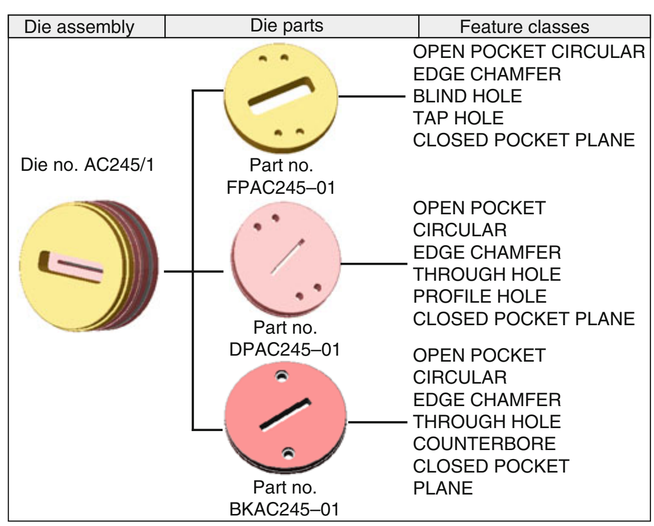

Fig. 1 Example of feature based extrusion die

approach. The main component is the die plate, whereas the back plate and feeder plate can be shared with different die plate in the same class. The case library is normally organized together with case-based reasoning which is explained in the next section.

4 Case-Based Reasoning Method

The concept of case based reasoning can be defined in the way to organize information or data, and this concept is applied to either 'idea', innovation or any other kinds of information that is to be stored and used in the future. Case-based reasoning (CBR) has applied to several domains. Design is one of the areas which is used in order to reduce design lead time together with to capture knowledge from experts and reuse such knowledge when the experts are not available. The basic idea of case-based reasoning is that new problems can be tackled by adapting solutions that were used to solve previous problems [7]. It is shown by many papers that are more efficient to solve problems by using previous similar solutions than to generate the entire solutions from scratch. The example applications are in the areas of architecture design [8], in chemical process engineering [9], and in mechanical design [10] as well as design for mass customization [11] etc. CBR consists of four main elements; case problem identification, case retrieval, case adaptation, case storage. All of the cases are linked to data case library that is accepted as knowledge-based library. In addition, there are another two components that assist the case retrieval and the case adaptation. They are case indexing method and case modification rule respectively.

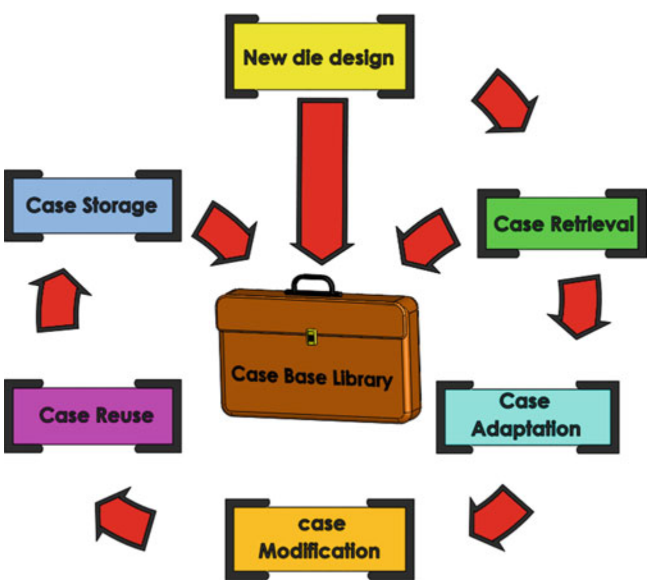

Fig. 2 Cycle of case-based reasoning (CBR)

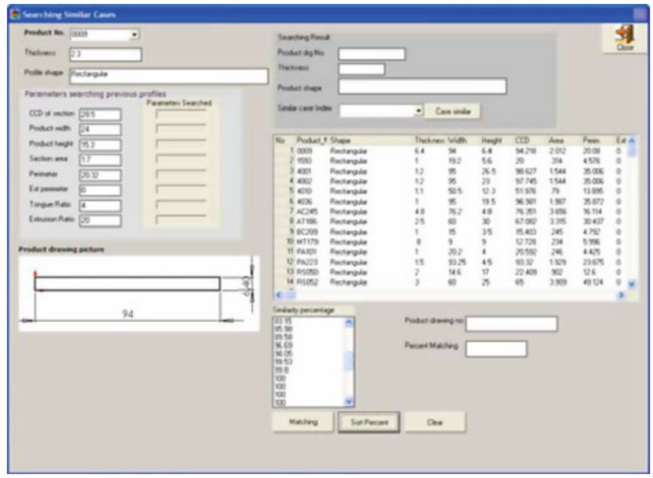

Fig. 3 Feature comparison and matching

Figure 2 shows the cycle of case-based reasoning. Primitive cases of die features are collected and stored in the case library. Such die features are classified and indexes in order to simply retrieve whenever it needed. New die design attributes are identified and put into the CBR cycle. The case retrieval is matched and retrieved the same or similar die features. If the same die is fortunately found, it will be adapted and used for the new die design. If it is not, the similar cases are taken into account. The most similar die is selected and adapted. It is then modified by an expert designer. The modified die is tested and reused for the new order in the extrusion process. The successful and failure are observed as well as recorded inside the case library for the future use. Figure 3 shows the case-based reasoning program which has been developed by Visual Basic which links to a MS access database and CAD (Solidworks©). The new aluminum profile is drawn on the CAD and export to the CBR program with it attributes. They are thickness, width, height, CCD, section-area, perimeter, tongue ratio, and extrusion ratio.

The program output shows the matching result in the degree of percentages. The most similar case or the most desire is selected. This program is able to bring the user to access to the CAD automatically in order to do a modification. Although, the CBR method is helpful, it can associate on the symbolic pattern matching. The significant numerical parameters are loosed. Therefore, the ANN method is considered to corporate.

5 Adaptive Parameters With Artificial Neural Networks

Artificial neural network is a mathematical model for parallel computing mechanisms as same as biological brain. They consist of nodes, linked by weighted connections. Neural

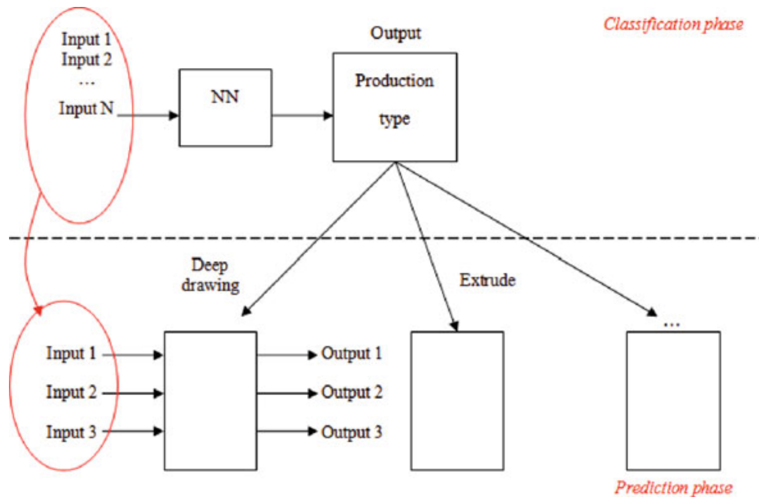

Fig. 4 Hierarchy of neural network procedure

networks are constructed by hierarchical layers, which are input, hidden, and output layer respectively. Neural networks learn relationships between input and output by iteratively changing interconnecting weight values until the outputs over the problem domain represent the desired relationship. Praszkiewicz [12] purposed the application of neural network to the determination in small lot production in machining. A set of features considered as input vector and time consumption in manufacturing process was presented and treated as output of the neural net. Scholz et al. [13] presented case-based reasoning for production control with neural networks, whereby expert knowledge about neural production control could be processed and structured in such a way that control strategies and according to, the applicable and adjusted neural networks could be selected and implemented for new production situations. The case-based reasoning enables the output of a solution for existing cases or the adding of new cases of neural production control.

Figure 4 shows the hierarchy of neural network procedure when it is applied to assist the CBR. There is divided into two steps. The first step is performed for classification, whereas the second step is used for prediction. The first result is considered together with the new data input. The classical concept of ANN is explained as the followings.

The mathematical model of the biological neuron, there are three basic components as presented in Fig. 5. First, the synapses of the neuron are modeled as weights. The value of weight can be presented the strength o the connection between an input and a neuron. Negative weight values reflect inhibitory connections, while positive values designate excitatory connections. Second component is the actual activity within the neuron cell. This activity is referred to as linear combination. Finally, an activation function controls the amplitude of the output of the neuron. An acceptable range of output is usually between 0 and 1, or –1 and 1.

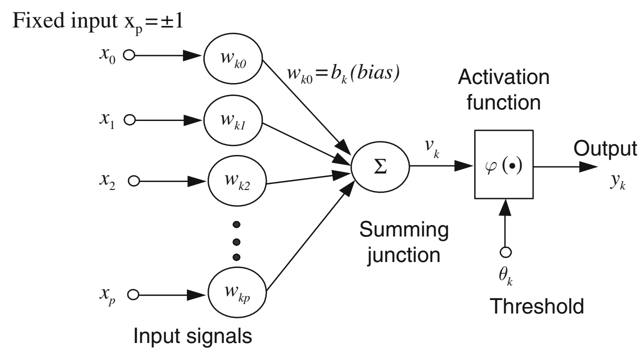

Fig. 5 A perceptron neuron model

Each neuron calculates three functions. The first is propagation function as shown in Eq. (1),

$$v_k = \sum w_{kj} x_j + b_k \tag{1}$$

where w_{kj} is the weight of the connection between neuron k and j, y_k is the output from neuron k, and b_k is the bias. The second is an activation function. The output of a neuron in a neural network is between certain values (usually 0 and 1, or –1 and 1). In general, there are three types of activation functions, denoted by $\phi(\bullet)$. Firstly, there is the treshold function which takes on a value of 0 if the summed input is less than a certain threshold value (v), and the value 1 if the summed input is greater than or equal to the threshold value.

$$\varphi(v) = \begin{cases} 1 \text{ if } v \geq 0 \\ 0 \text{ if } v < 0 \end{cases} \tag{2}$$

The proposed structure of neural network for die design and process planning is shown in Fig. 6. The input param-

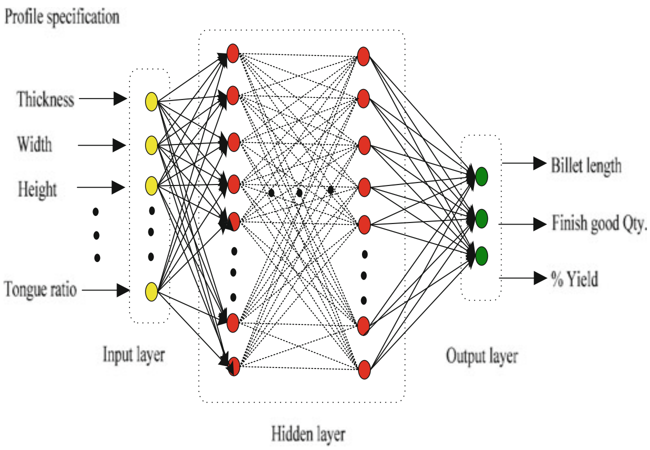

Fig. 6 The structure of neural networks

Table 1 The sample test input parameters

Item	Value
Thickness	2.3
Width	24
Height	15.3
CCD	28.5
Area	1.7
Perim	20.32
Tounge ratio	4
ER	20
Number of die hole	1
Extrusion ratio via number of die hole	20
Workpiece weight(Kg/m)	0.654
Backend length	8
Allowance	4
Finish good length	18

eters consist of the characteristics of aluminium profile including type of profile, profile shape, dimensions, cross-section area, extrusion ratio, CCD (Circumscribing Circle Diameter), tongue ratio etc. The output layer contains billet length, profile finished length and degree of yield.

The neural network has been trained by using the standard propagation algorithm. This work uses supervised learning, which is one of three categories of the training method. Supervised learning may be called associative learning, is trained by providing with input and matching output patterns. These input-output pairs can be contributed by an external teacher, or by the system which contains the neural networks (self-supervised). The learning process or knowledge acquisition takes place by representing the network with a set of training examples and the neural network via the learning algorithm implicitly rules. The topology of the proposed neural network model applies feed forward architecture. Each variable is the input value at a node of the input layer. The input layer of neuronal node is designed in such a way that one node is allocated for the feature type, and one node is allocated to each of the above sets of feature attributes.

Table 1 shows sample test input parameters, whereas the Table 2 shows the output parameters. There are three parts; actual data, prediction and errors. The ANN gives the best solution for extrusion process. It is clearly investigated that the actual yield is improved from 85 to 95% if the parameters are changed.

Figure 7 shows the training and learning process. There are 36 data are trained. The epoch is assigned by 1000. The best network is 616 epoch. The hidden layer is 6 layers. The error is 0.010586894.

Table 2 The output parameters

Actual			Prediction			% Error		
Billet length	Finish good qty	% Yield	Billet length	Finish good qty	% Yield	Billet length	Finish good qty	% Yield
13	5	85	14.11613	2.944283	99.31667	8.58	41.11	16.84

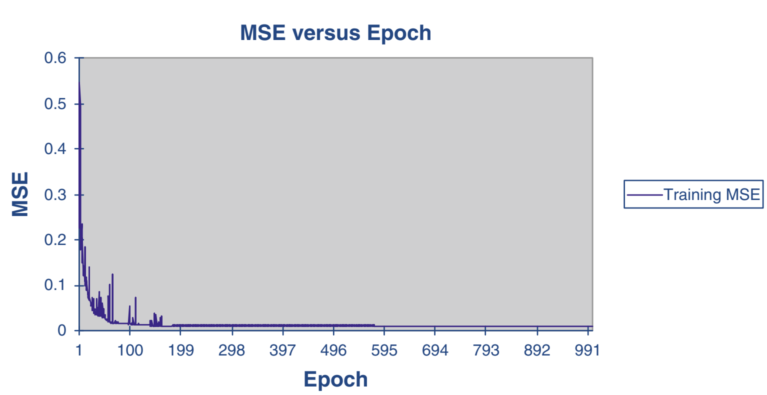

Fig. 7 The training and learning process

6 Summary

This chapter presents the methodology of case-based reasoning which is applied to adaptive aluminium extrusion die design on feature-based pattern matching. Instead of design from scratch, this approach search previous similar design problems and bring their solutions to solve current problems. However, the CBR is lack of dealing with numerical calculation and prediction. Therefore, this chapter is highlighted on applied the neural network to associate optimal extrusion processing parameters. It is clearly shown that the CBR is performed rapidly for feature die pattern matching together with the ANN can perform to give the best productivity of the yield.

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Knowledge Based Plants Layout Configuration and Piping Routing

P. Cicconi and R. Raffaeli

Abstract The design of industrial plants requires managing many geometrical and non geometrical data to reach a satisfactory solution in terms of costs, performance and quality. An approach is presented to support designers in the elicitation and formalization phase of the required knowledge. Then an integral prototypal software application accomplishes layout configuration tasks through a customized graphic wizard. A routing algorithm is presented to automate calculation and modelling of piping and electrical cables respecting design constraints. Cogeneration plant powered by micro gas-turbines has been chosen as test case to evaluate the proposed design method and tool.

Keywords Routing · Knowledge based systems · Knowledge management · Cogeneration · Computer aided plant design

1 Introduction

The increasing cost of traditional energy sources and the general sensibility to earth environment preservation have provided a strong push to renewable energy sources and to the minimization of losses and wastes. For many companies that means the birth of new business related to the design and installation of cogeneration plants which aim to reuse heat for conditioning while producing electricity on site.

In the layout definition of these plants, it is often mandatory to realize virtual prototypes to focus on solutions, costs, performances, parts arrangement and then prevent errors during installation phase. In this context routing problem is very important as it happens in many other fields such as electronics applications, navigation systems and computer networks. Basically, the principal design objectives are the correct dimensioning of parts, the convenient arrangement of plant components and the definition of piping or wiring following short and simple paths.

In many small design departments pipeline routes are still designed by two-dimensional CAD systems, with many limitations and pour design support. In the 1990 years, there was a push towards piping 3D design [1]. Nowadays, routing planning in a virtual three-dimensional environment has been further increased with the birth of piping specific tools for medium and high level CAD systems.

Main advantages of a parametric piping 3D modelling are:

- Virtual representation of working region boundaries.
- Exact obstacles definition.
- 3D model of each component: pipes, valves, filters, connections, engines, turbines, etc…
- Visible determination of physical interferences, accessibility and quality of paths.
- Easy printing of perspectives views and immediate understanding of plants also for non technicians (customers for instance).
- Rapid changing of dimensions with parametric features.

While the functional task is to transfer a specific volume of a fluid between two endpoints, a piping design problem is much broader and involves the definition of optimal route into a specific geometrical environment with assigned constraints. Routing problem is basically an iterative design task involving the geometrical definition of the given working space and a knowledge base of design rules and best practices.

Geometrical data are often provided as three dimensional models of structures, obstacles, routing search spaces, connects source and target terminals [2]. On the other side design knowledge is often unstructured and based on the experience of senior engineers. In fact, standard piping design supporting tools cannot support reasoning and incorporate limited automatic routing design features.

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Moreover existing tools support piping modelling and optimal equipments location but they do not offer an interactive configuration phase in which designer is helped in the layout arrangement.

Our research aims to define the framework of a knowledge based system to support the design, the configuration and modelling of plants in mechanical and industrial areas. To this aim, an approach to represent plants knowledge is presented along with relative data management tools. The approach for the configuration of the layout is based on the realization of a virtual prototype of the plant on the base of the Configurable Virtual Prototype (CVP) method already described in [3]. CVP stores knowledge of the product and supports configuration task.

In this chapter the approach is exemplified on cogeneration plants powered by micro gas-turbine [4], that are spreading after the advent of energy saving policies. This test case shows an example of equipment complexity in a small layout. A general knowledge formalization approach was required to outline a standard method in the layout design. Partner company knowledge was acquired in terms of data and rules and then represented in usable patterns. Finally a software tool is presented as a means to store and reuse the knowledge in everyday design activities.

2 State of the Art

2.1 *Piping Design Support Systems*

A general approach to aid the routing automation is still lacking and it has been the objective of many studies and commercial tools. There are specific system implementations in particular applications such as shipbuilding [5] and aerospace design [2]. These systems often are special advanced plug-in for CAD software but they can be used only in specific design contexts. For example, Dassault Systems is developing within Solid Works CAD system a routing tool for many years. Siemens has also introduced a similar tool in its widely diffused product SolidEdge. These packages are basically limited to the management of libraries of pipeline and electrical components and the introduction of easy features to model pipes and other parts of plants. Even if modelling support is valid, the real limits of these commercial applications are the lack of automatic routes generation, the impossibility to verify normative and to consider dimensioning formulas to predict plant performances.

In aeronautic and naval field tools has been developed for the specific application context [6]. In particular the focus was set in the quick update of electrical and piping systems after smalls changes in the main design structure. These are non commercial applications and are very specialized in specific design domains; therefore, it is difficult to reconfigure the tools and they risk becoming obsolete in a short time with the release of new models of aircrafts and ships.

Software known as Computer Aided Plant Design (CAPD) supports engineers to find an optimal arrangement of the process equipment in a generic plant like chemical [7], power generation and oil-gas plants. CAPD comprises software to design plants considering all involved aspects. These tools are very common in layout of flexible manufacturing systems, where the first objective is to optimize production flow from raw material to finished products. A generic approach to reduce "time-to-market" is developed in many of these applications, but this methodology does not support the configuration of power plants, where the primary task is system efficiency in accord to regional laws, normative and customer expectations.

Some commercial tools, such as "ACPlant design" by ACPlant USA Inc. and "AutoPLANT" by Bentley, have specific tools to energy management, piping design and building services engineering. In general, the most important features of a CAPD are: multi-CAD integration, efficient database management, flexibility to changes and user-friendly interface.

In conclusion, CAPD are specialized CAD-based tools to define layout, piping and structures, but they lack of databases which preserve knowledge from previous projects, engineer's experiences, analytical or heuristic rules to be used to come to reasonable decisions. These tools help the designer to model a solution but do not actively support the design phase.

2.2 *Knowledge Management*

Generally speaking, in accord to Polanyi research work [8], knowledge has a double aspect: tacit and explicit. *Tacit knowledge* is linked to individual experiences while *explicit one* is rational and sequential. Combining explicit and tacit forms, knowledge can be distinguished in five categories: conceptualization, reflection, experimental, transactive and expert [9, 10]. *Conceptualization knowledge* is the pure analytical one sourced from employed theory; *reflection knowledge* is linked to direct observation of empirical data; *experimental knowledge* investigates phenomena behaviour within certain boundary conditions starting from observational phase, with high validity; *transactive knowledge* is stored by individual group members and identify the existence and location of knowledge held by others; finally, *expert knowledge* is the tacit knowledge acquired by the experimental data.

Knowledge Based Systems (KBSs) are artificial intelligent applications to support the designer activity, imitating the human problem-solving and supporting decision-making, learning and action in complex problems. A KBS is a technology based on a database of knowledge and on methods to recognise similar situations. From the above categorization it emerges how KBS implementation requires suitable formalization approaches relative to the specific problem domains and type.

2.3 Solving the Routing Problem

In the literature many mathematical algorithms have been developed to solve routing task. In this paragraph some of them are recalled.

2.3.1 Shortest Path Algorithm

One of the main solutions to pipe routing is to find the shortest path between two points on the space using the graphical Dijkstra's method [11]. Yamada developed this method modelling a three dimensional geometrical space including the influence of pipelines [1]. His system does not find the best route but aides the designer to decide the optimal piping route with important information about the path length. This information is important since costs and pressure losses are directly proportional to path length. Anyway this approach neglects the curves effect.

Graphically each pipeline divides the plant space in different regions with boundary surfaces; mathematically bidirectional functions between pipelines and partition are established. A limit of this method is the little information about equipment and building structures.

2.3.2 Maze Algorithm

Lee's algorithm also known as *grid expansion algorithm* [12] is one of the earliest algorithm developed to enable automatic routing. The domain is divided by a grid of cells where the obstacles are marked with an *X*. The algorithm calculates the optimal route between two endings points having no interference with obstacles. This method assigns values to each node depending on distance from the target. Every maze algorithm guarantees a solution but it is not efficient, in fact it requires a lot memory and consequently it is very slow.

2.3.3 Escape Algorithm

This algorithm, also called *line-search algorithm*, generates the solution in a very fast way without much memory consumption, but it could not converge [13].

This iterative method calculates each line of a bi-dimensional path by extension of the end of the previous line along its direction. The iteration loop repeats the method until new line crosses the target point.

A algorithm*

A algorithm* is an evolution of maze algorithm. It is based on a grid path finder and used in computer game [14].

$$f(n) = g(n) + h(n) \tag{1}$$

This method gives a cost to each node, estimating a function $f(n)$ which sums $g(n)$, the distance function from the source, and $h(n)$, a heuristic estimated cost to the goal. The algorithm searches the nodes with lower score. A typical application is network optimization. The algorithm is an improvement of shortest path problem, so it does not consider costs, fluid dynamic performance, installation requirements, normative, etc...

2.3.4 Genetic Algorithm (GA)

A genetic algorithm approach was studied by Ito [15]. This method finds the optimal pipe route using an objective function. This function calculates the fitness value of a generic path of a set of candidate routes. Then, the best paths are combined with a crossover method to generate new piping route variants. The method is iterative and stops when the score reaches a target value.

The fitness function is based on: route path length, arrangement of the pipes under the same categories, maintenance spaces, number of curves and absence of interference with obstacles. For each aspect a range of scores is defined.

2.3.5 Cell-Generation Method

Park [5] developed an automatic pipe-routing algorithm based on cell-generation method. Geometrical domain is divided in a dynamic grid, in which cells are merged or split depending on pipe connection direction, pipe diameter and geometrical constrains such as interference, valve operability and safety. Park innovation is on an efficient division of the space, considering all geometric obstacles and operability spaces. The candidate path is selected including others non-geometrical aspects such as material costs and installation costs, so the algorithm exceeds the simply shortest path problem.

2.3.6 Minimum Installation Space

This method is used to develop piping in little and critical rooms, for example in airplane applications. In the research work of Drumheller [16], the objective of pipes routing is strictly linked to the minimum installation space.

2.4 Remarks

From the analysis of the routing algorithms found in the literature, the most complete method seems to be the genetic algorithm. In fact the fitness function may introduce many useful conditions like shortest path, low drop pressure, lack of interference, minimum workspace and so on. A weakness of GA in routing problem is the possibility of long calculation time. On the other side the fastest is the Escape algorithm, but it does not consider the conditions which are present in GA and Cell-generation method.

None of the presented algorithm combines a strategy in searching the optimal path with the knowledge of the particular problem being solved. Solution are reached only on the base of geometrical constrains. In this chapter, solution is guided by the specific plant design and related knowledge.

In particular, the routing algorithm employed for the test case is an evolution of escape one, in which paths are calculated considering performance, normative and geometric constraints. Optimal solution is searched by iterating loops.

3 Approach To Layout Knowledge Management

A knowledge based approach has been required to formulate a generic methodology to manage the layout configuration. Knowledge acquisition is often based on the analysis of interviews with experts and the gathering of experimental tests. Therefore it is necessary to elicit knowledge, convert the tacit to explicit one and formalize it. As described before, knowledge formalization process can have five different forms which are complimentary one another.

In this research, knowledge has been at first classified in different domains, each of them formalized in specific ways (Fig. 1). The eliciting phase has been focused on *who* or *what* were the depositaries of knowledge.

3.1 Gathering of a Knowledge Base for Layout Configuration

Coming to the specific knowledge required by layout plant design, it has been classified in four domains: configuration, geometry, normative and performance. In particular, Table 1 reports an example of information gathered for the cogeneration specific application field.

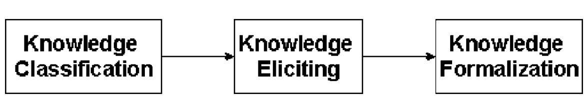

Fig. 1 Plants design knowledge eliciting process

Table 1 Micro co-generation plants design knowledge domains

Knowledge domains	Description
Configuration domain	Setup type, fuel type, placing type, machines number, components, etc...
Geometrical domain	Planimetry, geometrical boundaries, physical obstacles, interference detection, minimum workspace, etc...
Normative domain	Components dimensioning, normative requirements, local laws.
Performance domain	Fluid dynamics performance, electrical power, thermal power, thermo fluid dynamics efficiency, pressure losses, etc...

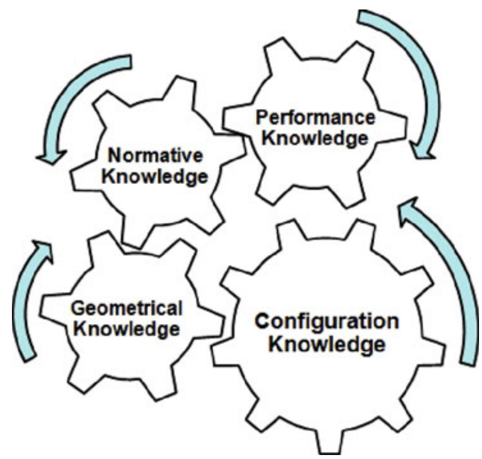

Fig. 2 Knowledge domains interdependency

Figure 2 shows the connection between the four levels of knowledge. The gearbox representation is a similitude of the iterations among the domains. While configuration level is the prominent aspect, the final motion transmission, which represents the designing layout, depends also on geometrical, normative and performance balances. In a linear transmission each gear is fundamental for the final output. Even if geometrical and normative knowledge interact, normative often is as a sort of layout verification. All levels are necessary for a highly customized result which has been found to be the most important characteristic of the design process. Therefore, an effective design supporting system should provide an outlook on all these aspects. Information gathered for each domain is now briefly discussed.

3.1.1 Configuration Knowledge Domain

This domain gathers product specifications, market requirements, functional requirements and concept solutions. It emerges basically from company experts background. It concerns configuration typologies, components, options, etc. . ., but it also contains rules for components selection and components relations.

Five levels of configuration design have identified in this research: setup type (*power, cogeneration, three-generation*), fuel type (*natural gas, methane, diesel*), placing type (*indoor, outdoor*), machine number, components (*selection, data, assembly rules*).

Configuration knowledge is an analytical explicit knowledge, such as for instance setup type and fuel type. It can be recovered on books and products specifications. On the contrary relations between components derive from experts knowledge. So assembly rules and components choice have a tacit nature and have been extracted during technical meetings with the people of the design and production departments.

3.1.2 Geometrical Knowledge Domain

This knowledge manages geometrical data along with expertise rules. Data are represented by walls planimetry, components and obstacles position of the installation building. Rules refer to interference detection and parts arrangement in order to guarantee a minimum workspace around plant components. Tacit knowledge about positioning of plant layout was elicited by technical workers, who are the responsible of plant final installation. Information gathered during talks with technicians has been formalized in geometric formulas and rules.

3.1.3 Normative Knowledge Domain

Laws and normative provides rules to guarantee a safe installation and operation of the plant. This kind of knowledge comes both during parts choice but also as verification of the obtained configuration.

Normative often presents a pure analytical knowledge, based on constraints, which is stored on official publications. This knowledge is normally readily available, but technical meetings have been useful for interpreting rules and laws in the specific design context.

This knowledge can be regarded as fixed and unavoidable. When opposite requirements emerge other domains indications must accommodate to meet the particular request of normative.

3.1.4 Performance Knowledge Domain

This aspect is a synthesis of conceptualization, system modelling, experimentation and expertise. Empirical and theoretical approaches mix to estimate plant performance.

Total performance is evaluated in terms of fluid dynamics performance, as noise or pressure losses, electrical power and thermal power outputs and related uncertainties. This knowledge has been formalised through diagrams, tables, formulas and corrective factors.

3.2 Knowledge Formalization and Representation

Class diagrams have been designed to formalize all knowledge domains following UML approach. These diagrams helped to organize gathered knowledge and were the base to develop the software tool presented in the next section. Classes have been populated with fields representing data selected in the knowledge base acquisition phase.

The *Configuration Class* (see Fig. 3) represents the global information relative to a certain plant. It includes and connects all other domains of knowledge, which are formalized in other separated sub-class diagrams. Configuration class holds all information about plant layout such as typology, fuel and performance. Main field is the components collection, which gathers all plant equipment. Component class manages many fundamental data such as: id code, category type, cost, geometrical dimensions and position, related codes, alternative options and the definition of parts compatibility.

A mixed of conceptual and expert knowledge has been collected. All components data are placed in datasheets, in which analytical data are explained with numeric values, rules are defined with text strings and compatibilities are expressed with Boolean checks (Fig. 4).

Layout configuration knowledge has been therefore formalized in standard classes, diagrams and tables. Information about general configuration, design parameters, components collection, plant performance, layout and geometrical data are included. Geometrical data provide dimensions and relative mounting positions of parts. Mathematical functions have been defined determinate lengths, areas, volumes, intersection, projections, rotations, translation, etc. . .

The following step of the approach has concerned the elaboration of graphical and non graphical means to let a generic user easily and intuitively interact with the data structure. A bi-dimensional graphical representation has been elaborated in order to capture a schematic plant layout. Graphic objects represent all main plant components in a simplified but exhaustive manner and are linked to the classes storing internal knowledge.

Each plant component links to internal data class which permits to edit principal characteristics, geometrical data, rules and custom functions through graphic forms.

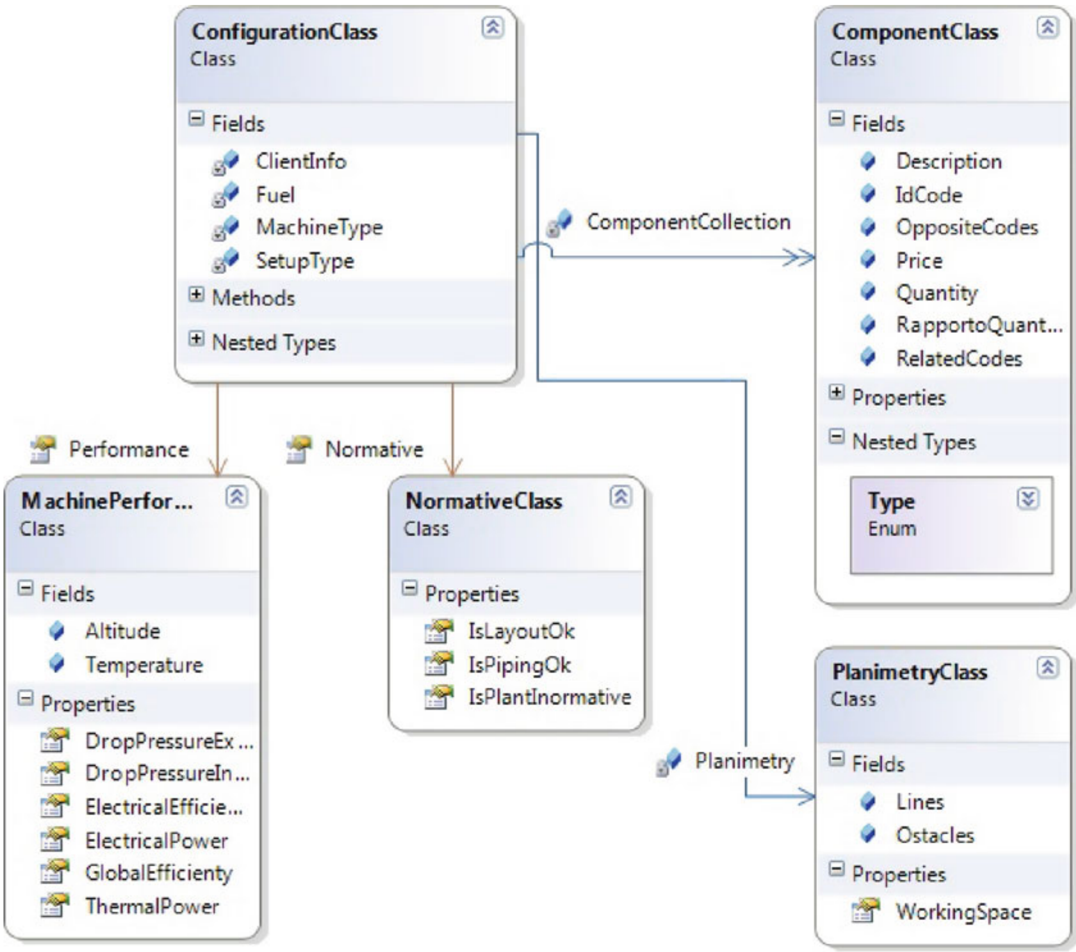

Fig. 3 Classes diagram tree representing layout knowledge

Descrizione	Rap. Q.tà	Prezzo Unitario [€]	Iva [%]	In Door	Out Door	Stand Alone	Gas Metano	Bio Gas	Diesel	Power	Cogen	Trig Ass
Turbina T100 Natural Gas	1	145000	20	☑	☑	☑	☑	☐	☐	☑	☑	☑
Turbina T100 Biogas	1	139000	20	☑	☑	☑	☐	☑	☐	☑	☑	☑
Turbina T100 Diesel	1	145000	20	☑	☑	☑	☐	☐	☑	☑	☑	☑
Outdoor Module	1	8000	20	☐	☑	☑	☑	☑	☑	☑	☑	☑
Outdoor Module Carpenteria	1	6500	20	☐	☑	☑	☑	☑	☑	☑	☑	☑
Outdoor Camini	1	1500	20	☐	☑	☑	☑	☑	☑	☑	☑	☑
Kit Staffa Ventilatore + Conn...	1	350	20	☐	☑	☑	☑	☑	☑	☑	☑	☑
Cover Plate	1	800	20	☑	☑	☑	☑	☑	☑	☑	☑	☐
Ventilatore Fan	1	600	20	☑	☑	☑	☑	☑	☑	☑	☑	☑

Fig. 4 Detail of the table capturing compatibility between components for each configuration option

3.3 Technology Employed for Knowledge Management

In this paragraph knowledge management technologies being used in this research are addressed. The main framework is an homemade data structure implemented by an object-oriented programming language (Microsoft VB.NET).

Knowledge management tools have been chosen in order to facilitate maintenance and usability of the software. Main data collections are stored in standard Microsoft Excel data sheets. Each sheet is organized in tables that store information about component attributes such as price, name, code, description, etc... User can easily update data without coding.

The main framework manages the connection with Excel by API libraries. A Configuration Class data structure is the container of geometrical and non geometrical data about the designed layout. Design rules are implemented in terms of IF-THEN-ELSE statements and components compatibility conditions.

Geometries are internally managed by 3D entities and represented on a two dimensional layout by using points, vectors, lines and polygons. The final 3D shaded plant layout is obtained by interacting with a feature based parametric CAD system using Application Programming Interface (API) based on COM technology.

4 System Implementation

The proposed approach has been developed in the context of layout configuration of micro-cogeneration plants. The core of such plants is the micro gas turbine "T100" produced by Turbec Spa a company of Ghergo Industry & Engineering Group (G.I.&E. Holding).

A windows-based application called "*MgConfigurator*" was developed in Microsoft VisualStudio.NET environment using Visual Basic.NET language to design and customize the installation of cogeneration plants. The application permits to configure all installation components and to build a two dimensional detailed representation. Finally it is possible to export the layout plant in the three dimensional environment of a widely diffused CAD system, SolidWorks 2009 by Dassault Systems.

4.1 Software Architecture

MgConfigurator has been implemented as a wizard structure, where a main container can alternatively load eight distinguished child forms.

Each child form has a basic structure but shows specific data and functionalities. Also graphical elements are different but share a common data structure. That means these forms could be considered as interrelated tools operating on the layout project from different design perspectives. Here follows a description of each tool.

1. *Product general configuratiion tool*

The configuration tool is the first step of a layout configuration (Fig. 5). This module allows defining the main configuration features as setup type, fuel type, machine number and placing mode. The first selections are filters for the automatic components choice.

2. *Components choice tool*

Second step is the components selection through a data grid view control. The application is able to preselect a standard list of component on the base of the features chosen in the

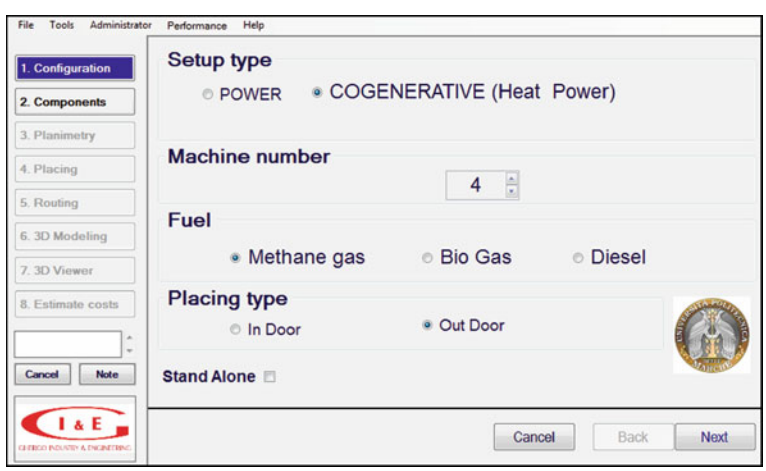

Fig. 5 First step of configuration wizard structure

first step. This tool reads configuration data and compatibility rules from data sheet and guides user to a right selection of components and options.

3. Planimetry tool

A graphical panel has been implemented to visualize the installation area of a plant. It is possible to import the geometric local plant from a *.dxf* file or from a sketch feature of a Solid Works document. A wireframe representation is used for the walls. Then predefined graphical controls to represent obstacles, windows and doors present in the real installation area can be added.
It is also possible to import curved walls that are approximated by polylines.

4. Component placing tool

The components layout is defined in a fourth tool called *Placing*, in which the user can manage graphical controls representing turbines, compressors, co-generators, etc... Each control has fields with specific data about pipeline connections; so flanges types, 3D positions and directions are available for the specific component position. The user has to specify the external connections with similar graphical controls for correct piping endpoints detection.

5. Routing tool

In the routing tool mathematical and iterative functions have been implemented to calculate routing paths of piping and electrical cables. The visual result is a bi-dimensional graphical visualization, but the software manages a collection of 3D nodes.

6. 3D Modelling tool

To export 2D visualization in a more comprehensible 3D one, a software module able to connect Solid Works 2009 CAD system has been developed. Parametric models templates have been designed to represent each component in a 3D environment. Routing paths are modelled from the mean axis definition through a sweep feature.

7. 3D Viewer tool

A viewer tool has been integrated in the software system to visualize the result of the 3D plant after the generation in the separated CAD system. This module includes the OCX control "eDrawings Viewer".

8. Estimated cost tool

Layout plant design process is completed by the estimation of the cost, which is computed as the summation of components cost and piping cost. The first one is the components cost sum while the second one is derived from necessary pipe spans length and curves.

4.2 Routing Approach

The routing tool is one of the main features in MgConfigurator. All available routing types are:

- *Intake duct*: to inlet air to combustion and to refrigeration;
- *Ventilation duct*: to remove hot air from turbine cabinet;
- *Fuel duct*: to provide fuel for combustion;
- *Evacuation gas duct*: for safety evacuation of non necessary gas fuel;
- *Water ducts*: to transport hot and cold water in cogeneration and tri-generation plants.
- *Electric cables*: for electricity management.

The principal task of the routing interface is the calculation of three-dimensional routing paths, avoiding any physical interference with other components and with geometrical boundaries.

In this work the path is calculated from coordinates and directions of the endpoints, without implementing static templates of simple routes. Every complex route is split in n-routes. Generation function evaluates possible interferences and goes around each obstacle found along the path working in a 3D space (Fig. 6).

In particular main input data for a route generation are taken from the plant configuration class: geometrical definitions of extremes points (3D coordinates and directions),

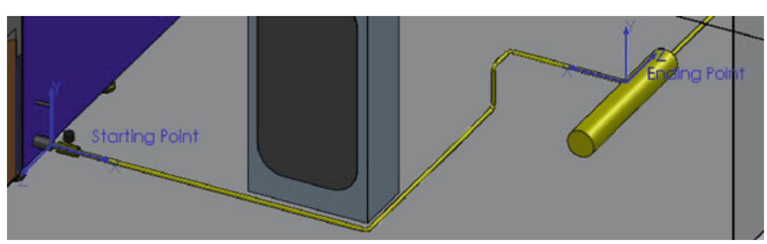

Fig. 6 Example of a route avoiding an obstacle

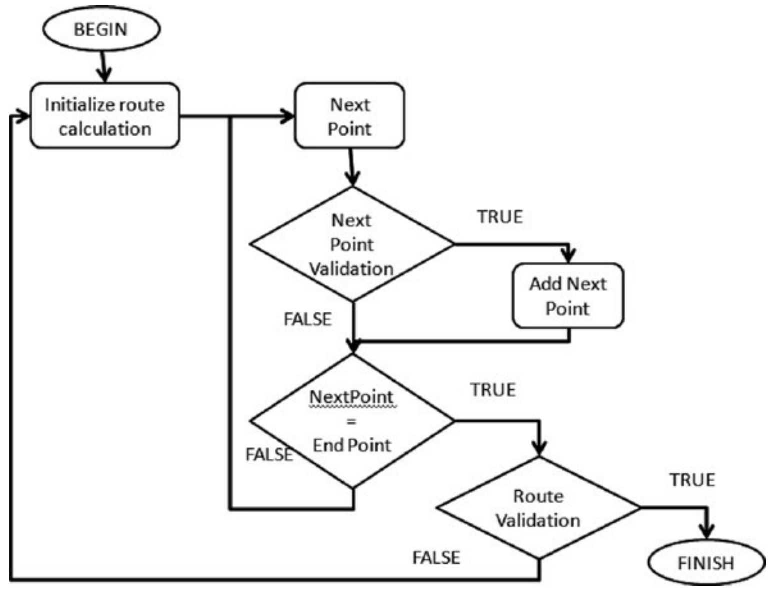

Fig. 7 Block diagram of routing calculation algorithm

route type (air intake, gas exhaust, fuel, etc…), reference normative, the definition of installation space (dimensions), obstacles and components (position and dimensions).

The proposed approach is based on a double iteration algorithm as schematically shown by the block diagram in Fig. 7. The first external cycle generates a complete route path until it is valid and matches all design constraints. The internal iteration cycle calculates each nodes of a single route until the final extreme is reached.

The generation of each point is determined by assigning scores to the principal directions as a function of their distance from the endpoint. The point validation is based on the condition of no interference. Similarly the validation of route depends on normative and on acceptable fluid dynamic performance which is mainly connected to path length.

The particular iteration approach allows generating many different correct candidate paths and then selecting the most performing one on the base of total cost or total fluid dynamic losses.

4.3 Routing Algorithm

The algorithm described above has been implemented by VB.Net programming language. Main loop of the program illustrating the basic steps of the algorithm is reported in Fig. 8.

The code is completed by the implementation of the required sub functions and with a control on infinite loops avoidance. In worst cases after a defined number of cycles, the algorithm escapes without a solution.

In the algorithm the most relevant functions are the computation of intermediate route nodes and interference detection and correction.

4.3.1 Calculating Path Intermediate Points

A function defines coordinates and direction of each intermediate node incrementally while calculating the whole path. At each step six candidate directions are considered which are aligned to main coordinate axes; a score is assigned to them considering current direction and distance from final extreme point. In the approach score assignment is a particular fuzzy random function. Directions toward target have a relative high scores, while opposite ones receive low scores; in this way directions with higher score becomes more probable but other directions are not completely discarded. The basically random aspect allows the calculation of different points for each cycle; so many acceptable solutions can be found iteratively.

4.3.2 Interference Detection and Correction

While computing path a function is delegated to check interference. This function compute a bounding box to each layout plant component: walls, doors, obstacles, turbines, etc…; if a line of a route intersects the volume of a bounding box, then the interference is detected. The approximation of a component with a bounding box is normally acceptable for the geometries being involved and guaranties high algorithm efficiency.

Fig. 8 Main loop instructions of the proposed routing algorithm

```
eCount = 0
Do '
    eCount += 1 ' external iteration counter
    IsRouteValid = False 'default route validity
    'inizializing
    oldPoint = startPoint : actualPoint = startPoint : nextPoint = Nothing
    iCount = 0 'internal iteration count
    Do 'iteration to generate new straight line of route
        iCount += 1 ' second internal counter
        IsLineValid = False 'default line validity
        'next point and direction compute
        Me.NextPointCalculation(nextPoint, oldPoint, actualPoint)
        Dim line As New LineRoute(actualPoint, nextPoint)
        'interference detection
        If Not Me.InterferenceVerify(line, workingSpace) Then
            IsLineValid = True
        Else
            'interference correction
            If Me.InterferenceCorrection(line, nextPoint, workingSpace) Then
                IsLineValid = True
            End If
        End If
        If IsLineValid Then
            route.Add(line)
            oldPoint = actualPoint
            actualPoint = nextPoint
            nextPoint = Nothing
        End If
    Loop Until (nextPoint = endPoint) Or (iCount = exitCount)
    IsRouteValid = Me.RouteFinallyVerify(route, workingSpace)
Loop Until IsRouteValid Or (eCount = exitCount)
If IsRouteValid Then Return True
```

If interference is presented for a route line, a specific routine tries to reduce the length of the last segment within an iteration cycle. In interference is not eliminated after a certain number of iterations, a new path is recalculated.

4.4 From 2D to 3D Visualization

Using MgConfigurator, users can configure micro cogeneration plant layouts working on a bi-dimensional graphic editor (Fig. 9). So it is possible to manage piping, machines and equipments with 2D graphic blocks without any CAD interaction.

After layout definition, integration between CAD and MgConfigurator has been provided to automatically realise a 3D model of the plant. The automatic modelling is based on Solid Works API (Application Programming Interface) which allows a direct link with the geometrical modelling kernel. Custom programming libraries has been implemented to generate 3D model documents.

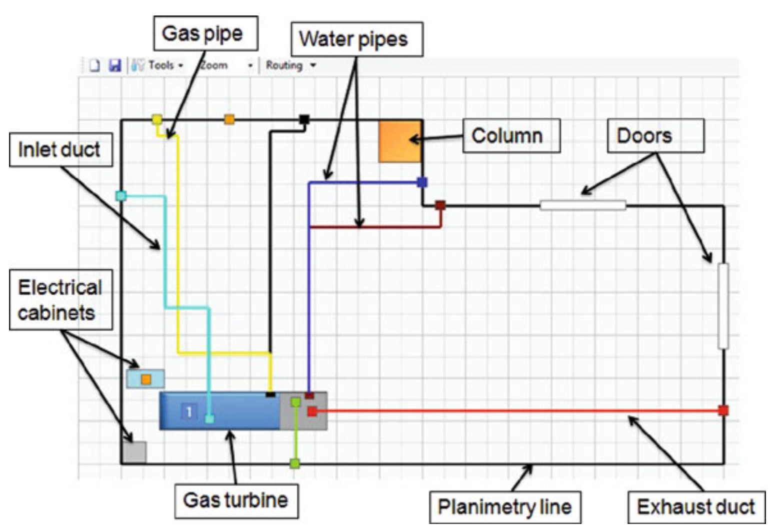

Fig. 9 Example of two-dimensional representation of a gas turbine layout

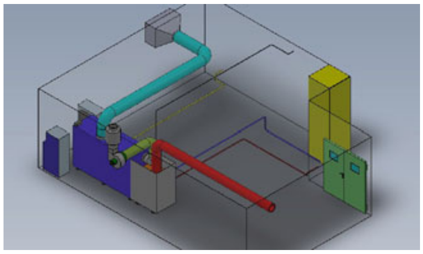

Fig. 10 An example of 3D plant generation

The 3D modelling tool generates assembly documents from parametric geometric data migrating internal geometries representation in a CAD document. Moreover this process is basically CAD independent and can be extended to other CAD systems.

Standard components CAD models had been interactively modelled and stored inside a database. In the plant assembly document generation parameters are updated to meet desired dimensions and parts located by coordinates read in the 2D layout. Moreover, application supports modelling of piping and electric wires starting from sketches through 3D sweep features.

An additional 3D viewer tool uses the OCX graphic control eDrawings, a multi CAD viewer included into Solid Works suite. This solution let the user evaluate the newly generated assembly model in a three dimensional space (Fig. 10), without using the CAD system. At this step it is also possible to generate drafts and send email with printed views. In conclusion CAD is exclusively used as modelling kernel and can also ran in a separate server machine. Then only one CAD licence is enough for many MgConfigurator installations.

4.5 Energy Performance Knowledge Management

Knowledge about performance has been formalized in tables and formulas to evaluate energy power and efficiency. In particular in this section the calculation of piping pressure losses and of global performance is briefly illustrated.

4.5.1 Piping Pressure Losses

Energy losses in pipes decrease the nominal performance of standard plants. So piping design requires fluid dynamic analysis to estimate pressure drop. In linear pipes losses has been computed using fluid dynamic Darcy-Weisbach formula (2), which links pressure loss (ΔP) to friction (f) along a given length of pipe (L), on an average velocity (V) of the fluid flow, with a fixed diameter (D).

$$\Delta P = f \cdot L \frac{V^2}{2 \cdot D} \cdot \rho \tag{2}$$

The friction factor f is not a constant, but it depends on the parameters of the pipe and on the velocity of the fluid flow. It is known with high accuracy within certain flow regimes. For laminar flows f equals 64/Re, where Re is the Reynolds Number; for turbulent flow, friction factor f is found using a diagram such as the Moody chart or solving equations such as the Colebrook equation (3), where λ is the friction factor f, ε the roughness of the pipe and D the inside diameter.

$$\frac{1}{\sqrt{\lambda}} = -2 \cdot \log\left(\frac{2.51}{\mathrm{Re} \cdot \sqrt{\lambda}} + \frac{\varepsilon}{3.7 \cdot D}\right) \tag{3}$$

In MgApplication application a root-finding algorithm has been developed to iteratively calculate the friction factor λ using the Colebrook formula.

4.5.2 Performance

Plant performance depends on the number of gas turbine chosen at configuration phase. The manufacturer of turbines provides tables and graphs to determine the performance in terms of power and efficiency. Standard operating conditions and relative performances are reported in Table 2 for the specific test case.

Estimated power and efficiency must to be multiplied with corrective factors depending of altitude, temperature, drop pressure on the air inlet flange and on the exhaust flange.

$$P_{\mathrm{ele}} = f_1 \cdot f_2 \cdot f_3 \cdot f_4 \cdot P_{\mathrm{nom}} \tag{4}$$

The previous formula (4) shows that the effective electrical power is a function of nominal power by corrective factors explained in next Table 3.

Table 2 Operating conditions of Turbec gas turbine

Temperature	15°C
RH	60%
Drop pressure (input-output)	0 Pa
Fuel (Natural Gas) PCI	39 MJ/m_n^3
Fuel supply pressure	0.02–1 bar
Altitude	0 m
Electrical power	100 KW
Electrical efficiency	30%
Thermal power	165 KW
Global efficiency	80%

Table 3 Corrective factors about electrical power

f1: altitude rate	0.82–1.00
f2: temperature rate	0.90–1.00
f3: drop pressure inlet intake rate	0.87–1.00
f4: drop pressure exhaust rate	0.87–1.00

5 Test Case Plant

In this section an example of plant which has been configured with "MgConfigrator" is presented. The layout is an outdoor installation with four co-generative micro gas-turbines powered by natural gas. General configuration data were inserted in a primary form as in Fig. 5 and then necessary components detailed in the following steps.

The geometrical layout was configured by the dedicated graphics editor shown in Fig. 11. It contains the machines (numbered big blocks), column (blocks at the corners), the planimetry drawn by boundary black lines, principal electrical cables (oblique lines), hot water circuits and cold water circuit. Piping has been generated automatically using the software functionalities. Finally Fig. 12 shows the plant isometric view, which was automatically generated by "MgConfigurator" in about 1 min.

In Table 4 the comparison between performance evaluated data from the knowledge based application and the real tested value are shown.

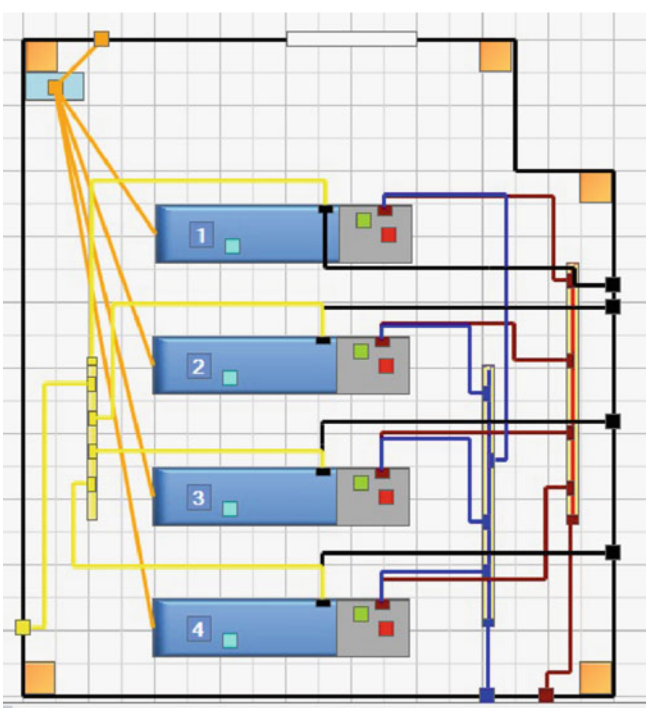

Fig. 11 Bi-dimensional test case layout plant

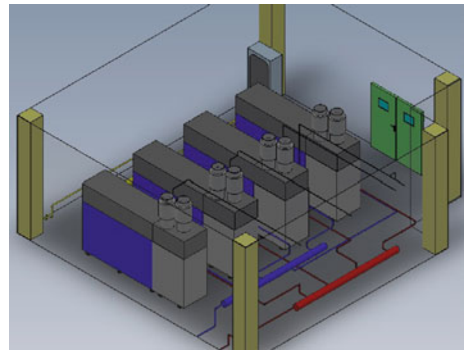

Fig. 12 Isometric view of configured outdoor cogeneration plant

Table 4 Evaluate and tested performance

Performance	Evaluated	Tested
Electrical power	293 KW	386 KW
Efficiency power	29.5%	29.1%
Thermal power	652 KW	644 KW
Global efficiency	79.8%	78.7%

6 Conclusions and Future Developments

This work has presented a knowledge base framework reusable for the configuration task of plants. In particular it has presented an approach to support the technical configuration phase and the geometrical layout definition of industrial plants, with a particular attention to routing problem of piping. A Windows application has been developed based on a user-friendly wizard interface to guide the user in a complete layout configuration. A bi-dimensional blackboard editor has been employed to manage parts of layout plant. The knowledge based application was implemented as a standalone tool but can interact with a CAD system for 3D models generation exploiting the API libraries of Solid Works.

The future development of this work will be the integration of local database with company PDM tools, the improvement of estimated plant costs and a link to more CAD systems. Finally it is important to extend and test the proposed approach to different type of plants managing specific fields of knowledge.

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An Interactive-Based Approach to the Layout Design Optimization

J. Bénabès, F. Bennis, E. Poirson, and Y. Ravaut

Abstract Layout design plays an important role in the design and usability of many engineering products and systems. Because of the great complexity of most industrial layout problems, the decision of the acceptable layout is a hard and critical task since the special layout can have a significant consequence on the global performances. Thus, in order to propose to the designer an optimal spatial arrangement in a reasonable time, this chapter develops an interactive optimization strategy that is tested on the facilities layout problem of a shelter. This problem is innovative because it introduces the concept of space of accessibility

Keywords Layout problem · Interactive optimization · Genetic algorithm

1 Introduction

Layout problem is inherently a multidisciplinary task [1]. It covers all the aspects of the product design life cycle from the conceptual to the detailed stage and makes necessary the collaboration between experts of technical and economical disciplines. In fact, layout design is usually formulated as an optimization problem: *find the best arrangement (location and orientation) of components in a given available space satisfying geometrical and functional constraints*. A non-overlapping constraint is basically a common geometrical constraint for all 3-Dimensional Layout problems, while alignment, orientation or gathering components refer to functional constraints. Because of the geometrical complexity, the 3-Dimensional layout problem optimisation is non-linear and NP-hard. It means that the problem is intrinsically harder than those that can be solved by a nondeterministic Turing machine in polynomial time. The objective and constraints evaluation is generally time consuming.

It is essential to distinguish between Cutting and Packing (C&P) problems and 3-Dimensional Layout problems. In C&P problems, components are only geometrically related to each other, whereas in layout problems, components are geometrically and functionally related and connected. This difference leads different tools and methods to solve each class of problem being aware of the common non-overlap constraints in the two problems.

Typologies of C&P problems have been proposed [2] but as far as we know, there is no general typology of layout problems. Amine Drira et al. have described a tree representation of facility layout problems [3] that depends on design constraints and objectives of the location of facilities inside a plant.

Actually, layout problems can be divided into several kinds of specific problems, which have their own solving method. C&P problems can be assimilated as a particular application of each specific problem.

Layout problems can also be classified according to three criteria: the compactness of the problem, the number and type of design constraints and objectives and the geometrical complexity of the design components. For example, the container loading problem and the engine layout design are not in the same category of problem. It means that, for the two problems, the compactness is important but in the engine layout design, constraints and objectives are multiple (non-overlap and functional constraints, accessibility objective...) and the different parts of the engine have complex lines. The container loading problem does not have the same characteristics.

The formulation of layout problems uses mono-objective or multi-objective optimisation. The designer can make an early decision by using an aggregation function in order to transform a multi-objective into a mono-objective one. This approach is only effective when all data and information on the aggregation are available or if the designer is familiar with the specific layout problem. In this chapter, we

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use multi-objective optimization. The decision on the preferences between objective functions is delayed so that the designer can use the Pareto-front in order to select the most appropriate solution. In this approach, the designer has to simultaneously optimize two or more conflicting objectives subject to constraints.

The general formulation of an optimization problem can be written as the Eq. (1), where m is the number of objective functions and n the number of design variables.

$$\begin{cases} \text{find the design variable } \mathbf{x}^* = (x_1, x_2, ..., x_n) \\ \mathbf{x}^* = \operatorname{argmin} F(\mathbf{x}) = (f_1(\mathbf{x}), f_2(\mathbf{x}), ..., f_m(\mathbf{x})) \\ \text{s.t: } g(\mathbf{x}) \leq 0 \text{ and } h(\mathbf{x}) = 0 \end{cases} \quad (1)$$

The designer has to compare two solutions represented by two vectors of objectives $F(U) = (f_{1U}, f_{2U}, ..., f_{mU})$ and $F(V) = (f_{1V}, f_{2V}, ..., f_{mV})$ where f_{iU} is the ith component of the vector of objectives F for the design variable U. In fact, U dominates V (Pareto dominance) if U is as good as V for all the objectives and U is better than V for at least one objective. Mathematically, this can be formulated by:

$$\begin{cases} \forall\, i \in [1, ..., n]\; f_{iU} \leq f_{iV} \\ \exists j \in [1, ..., n] f_{jU} < f_{jV} \end{cases} \quad (2)$$

Multi-objective optimization searches for the set of non-dominated points (assimilated to Pareto-optimal points in the next sections of this chapter) in the objective space given by efficient solutions. Figure 1 represents the Pareto front for an optimization problem defined by two objectives ($\min f_1$, $\min f_2$) where U dominates V.

One finds multiple search algorithms to solve layout optimization problems in two or three dimensions. Traditional optimization approaches for three dimensional layout problems are described by Jonathan Cagan et al. [4]. They use genetic algorithms [5], simulated-annealing algorithms [6, 7] or extended pattern search algorithms [8]. Most search algorithms are developed for a specific problem and they provide an effective optimization strategy for this kind of problem. Therefore, they are not generic and can not be adapted to other layout problems. In this chapter, the proposed method is based on a generic technique for solving layout problems. The design strategy uses a Genetic Algorithm coupled with a Separation Algorithm, in order to ensure a good diversity of solutions computed by the algorithm, and allows the designer to interact with the Pareto-optimal solutions.

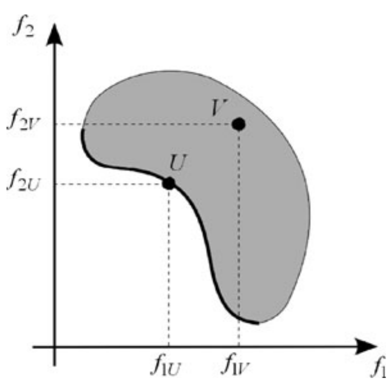

Fig. 1 Pareto front of a multi-objective problem

This chapter is organized as follows: in Sect. 2, the synopsis of the proposed optimization method is presented. In Sect. 3, the proposed method is tested on the layout problem of facilities inside a shelter. Optimization problem formulation and results obtained by the method are described and analyzed. Sections 4 and 5 are dedicated to an outlook on future work and the conclusion.

2 Problem Solving Strategy

The constraint space of design variables is highly composite because of the geometric complexity, the non-overlap constraints and the relative location between the components. This property leads us to recognise that there is no choice but using stochastic or heuristic techniques for a 2-D or 3-D layout problem. This kind of technique makes it possible to explore efficiently the design space and avoid a local optimum. We also recognise that a multi-objective Genetic algorithm is suitable for this problem.

Basically, a genetic algorithm search uses the mechanics of natural selection and natural genetics to evolve a population of initial solutions into a near-optima solution. The common idea behind these algorithms is the same: given a set of individuals from an initial population, the genetic algorithm uses basically 3 operators in order to create a set of new candidate solutions. This process can iterate until candidates with sufficient good fitness are obtained. The three operators are namely: selection, mutation and crossover or recombination. Mutation and recombination act to create the necessary diversity and novelty and selection acts as a force of pushing quality (fitness). Repeated selection from the same population would produce nothing better than multiple copies of the best individual originally in it. For improvement to be able to occur, some novelty must be introduced into the population between selection steps. The genetic operators modify the selected parents by manipulating their genotype.

Since the genetic algorithm is based on stochastic operators and parameters, the progression of multi-objective layout optimisation is time consuming. It depends also on the number of design variables and the number of components and the types of design constraints. In order to improve the algorithm we introduce two new steps into the global process of the genetic algorithm: separation techniques and interaction with the designer. The initial random population of the GA is improved using the separation technique and interaction. In fact, the initial random population of the GA leads to a high number of overlap components thus the GA fails to find efficient candidates.

The objective of the search algorithm proposed in this chapter is to generate a uniformly distributed global Pareto front for layout optimization problems. Our strategy consists of initializing the multi-objective optimizer with a population of individuals which have been locally modified by a separation algorithm and designer interaction in order to reduce the violation of placement constraints. Thus, the strategy is based on three complementary approaches, which are clearly separated:

1. Firstly, the generation of a database of mixed designs which respect non-overlap constraints.
2. Secondly, the optimization of this database by considering all the design objectives (with a Genetic Algorithm).
3. At the end of the GA iteration process, the interactive choice of the suitable solution by the designer is conducted using the non dominated Pareto front generated by the GA.

2.1 Separation Algorithm

Several separation algorithms have been proposed [9, 10]. However, the key idea is always the same: given a configuration that doesn't satisfy location constraints, the objective of the separation algorithm is to minimize the non-respect of overlap between components and protrusion (overlap between components and the non allowed space).

For solving simple layout problems in two dimensions, the separation problem is formulated as an unconstrained minimization problem defined by:

$$\text{(Sep Algo)} \begin{cases} \min F(x) = \sum A_{ij} \\ i,j \in [1,\ldots,n]\ ,\ i \neq j \end{cases} \tag{3}$$

where A_{ij} represents the intersection area between the components i and j. Consequently, it is possible to define the violation of placement constraints F as the total sum of intersection areas between the different elements which make up the layout design. For example, let us consider that all the items of the layout design are rectangles. The intersection area between two items is equal to:

$$A_{ij} = \max\left[0, \min\left(x_i + \frac{l_i}{2}, x_j + \frac{l_j}{2}\right) - \max\left(x_i - \frac{l_i}{2}, x_j - \frac{l_j}{2}\right)\right] \times \max\left[0, \min\left(y_i + \frac{L_i}{2}, y_j + \frac{L_j}{2}\right) - \max\left(y_i - \frac{L_i}{2}, y_j - \frac{L_j}{2}\right)\right] \tag{4}$$

where (x_i, y_i) are the coordinates of the geometric center of the rectangle i. L_i and l_i represent respectively the length and the width of the rectangle i.

The algorithm used to minimize F is based on the Broyden-Fletcher-Goldfarb-Shanno (BFGS) method. This algorithm computes a finite-difference approximation of the gradient and the hessian of the function F in order to locally modify the optimization variables and to minimize F. The algorithm stops after a certain number of iterations.

In order to understand the principle of the separation algorithm, let us consider a layout problem test. The dimensions of the square container are $10 \times 10 = 100\ \text{m}^2$. The objective of this 2D-configuration problem is to place N square items whose dimensions are $1 \times 1 = 1\ \text{m}^2$in the container. It means that the algorithm searches the optimal configuration that reduces the violation of placement constraints F, which has been previously defined as the total sum of intersection areas between the square items and the container. Figure 2 shows simulations results, considering different values of the problem density.

2.2 Multi-Objective Optimization

The multi-objective optimizer is in charge of exploring efficiently the search space to propose trade-off solutions. The proposed method uses the Multi-Objective Genetic Algorithm (MOGA-II) [11]. MOGA-II is an efficient Multi-Objective Genetic Algorithm (MOGA) [12] that uses a smart multi-search elitism. This new elitism operator is able to preserve some excellent solutions without bringing premature convergence to local-optimal frontiers. For simplicity, MOGA-II requires only very few user-provided parameters. Several other parameters are internally settled in order to provide robustness and efficiency to the optimizer. Three genetic operators are used to generate new solutions:

- *Directional Cross-over*: the cross-over operator is a method of recombination where parents produce offspring by sharing information. The aim of this operator is to obtain individuals with better characteristics while maintaining the diversity of the population.
- *Selection*: this value gives the probability that design configurations are not changed during the evolution. In order to maintain a good diversity between points, this parameter should be kept small,
- *Mutation*: this value gives the probability that a design configuration is randomly changed.

For the application studied in Sect. 3, the genetic operators have been set as shown in Table 1. The number of individuals in the initial generation is equal to 240 because a rule of thumb suggests the possibly to accumulate an

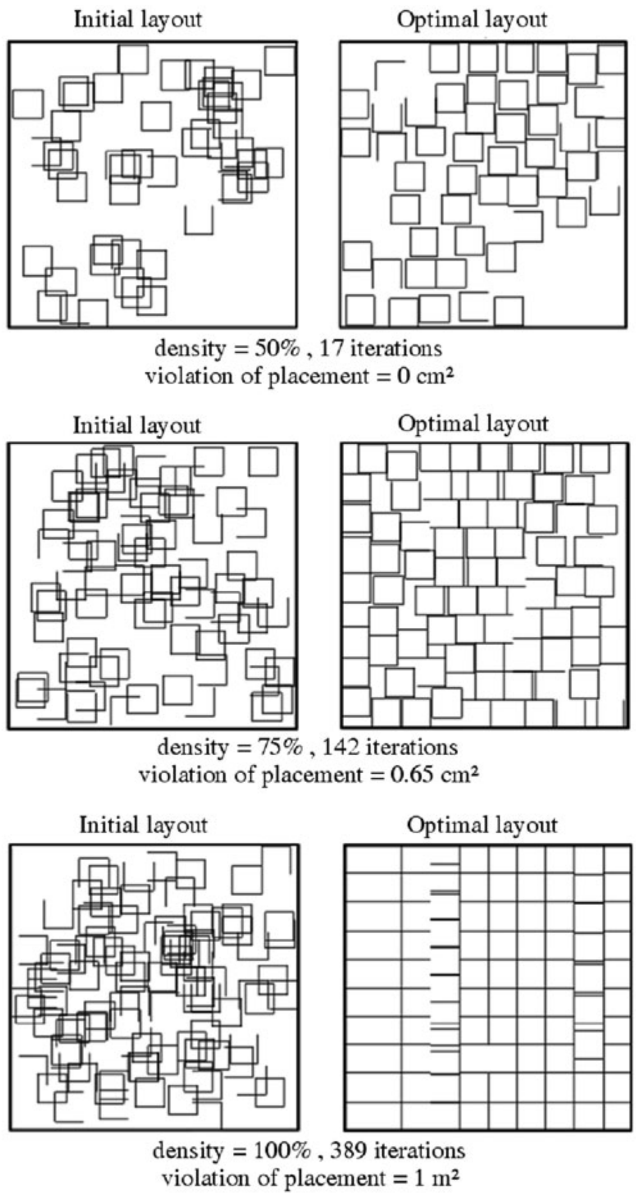

Fig. 2 Separation algorithm BFGS test

Table 1 Multi-objective genetic algorithm parameters

Number of individuals in the initial generation	240
Probability of directional cross-over	0.1
Probability of selection	0.05
Probability of mutation	0.45
Probability of classical cross-over	0.4
Elitism	enabled
DNA string mutation ratio	0.5
Number max of generations	100

initial population of at least 16 design configurations and possibly more than 2 × Number of variables × Number of objectives $= 2 \times 24 \times 5 = 240$.

2.3 Interactive Process

In general the development of an engineering object is considered as a single process involving multicriteria identification of the mathematical model followed by multicriteria optimization of the object design on the basis of this mathematical model. The process of statement-solution of engineering design problems without the interference of the design is impossible. In solving the design problem, the designer almost always has to correct either the mathematical model, the dimension of the vectors of design variables and criteria, the design variable ranges, and so on. This creative process of correcting an initial statement is natural when solving engineering problems. The direct participation of the designer in the construction of the feasible design and non-formal analysis are the essential stage of the search for the optimal design [13]. The simulation tools provide powerful solutions for planning and designing of complex mechanical systems. The problem with these is the representation and the interpretation of the results by the engineer. Important for the engineer is not only the value of the point but its variation and the information about the most appropriate directions. The exploitation of the results is not obvious and the link with the performance value of the real phenomenon is not trivial. When one analyzes the communication between the operator and the computer, it can be perceived that the operator immersion in the digital model is very weak.

It was pointed out in Sect. 1, that the decision can be made earlier in the design optimisation process by the creation of an aggregation of the objective function or later using the non-dominated points generated by the genetic algorithm. The proposed strategy uses two interactive steps. The first one is the interactivity of the designer for the selection of feasible solution to present as an initial population of the genetic algorithm. The first interaction step is limited to the geometrical non-overlap of components. The GA algorithm can be stopped after a fixed number of iterations. Since all the non-dominated points are potentially good acceptable solutions of the given Layout problem, the designer has to explore the set of these points and select the best solution. It is well recognised by the expert of the optimisation that it is always very hard to express all the designer requirements using only the objective function. Several subjective functions are qualitative and can not easily be expressed explicitly by using a numerical value. In order to take into account this subjective aspect of the layout problem, selected solutions of the non-dominated front are presented to the designer and an interactive numerical environment is used to support the decision. Since the number of non-pareto points can be to very large, we also use a reduction approach that regroups all the equivalent solutions. Then for each presented solution, the designer can act on the environment and locally modify the position or orientation of the appropriate components. This step is different to the initial interaction since the designer has also the evaluation of all the objective function. The interactivity is not only limited to the geometrical visual evaluation but the value of the objectives function and there deviation are helpful at this step.

3 Application

3.1 Problem Description

In this section we consider an application of the proposed strategy to find the optimal layout of facilities in a shelter. Several components have to be arranged in the shelter including electric and energetic cabinets, desks and electrical boxes. The CAD model of the shelter is presented in Fig. 3.

The layout optimization of this shelter is a three dimensional optimization problem. However for the presentation, and fortunately because the cabinets are the full height of the shelter and prevent a superposition of elements, the model is simplified and conceptualized in two dimensions. The simplified model of the shelter is shown in Fig. 4.

The formulation of this layout problem is innovative because the components can be classified in two categories: those which have a mass *(material components)* and those which no have mass *(virtual components)*. Here, the virtual components represent the spaces of accessibility of the cabinets and the desks. For example, the space of accessibility of the cabinet is the required space to insert some materials into the cabinet. These spaces are symbolized in Fig. 4 by dotted rectangles. With this problem formulation, design constraints depend on the category of components. It means that overlap is allowed between two spaces of accessibility, taking account that operations of materials loading are sequentially made whereas overlap has to be minimized between two material components.

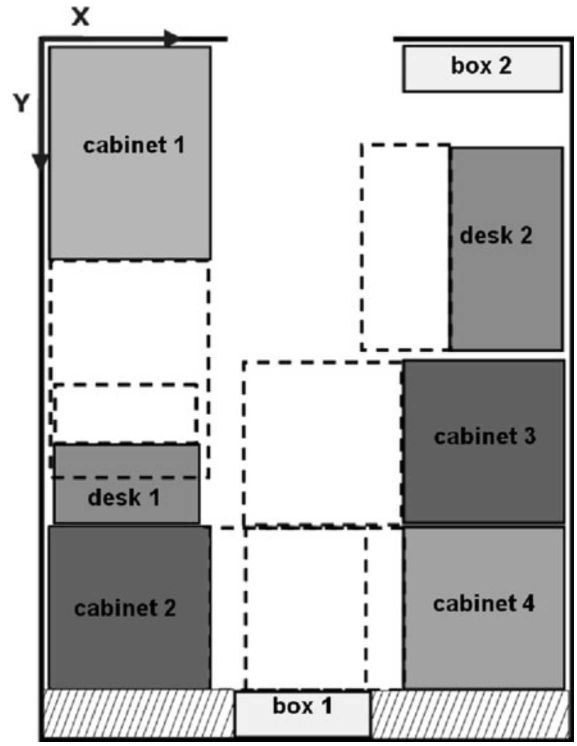

Fig. 4 Configuration model of the shelter in 2D

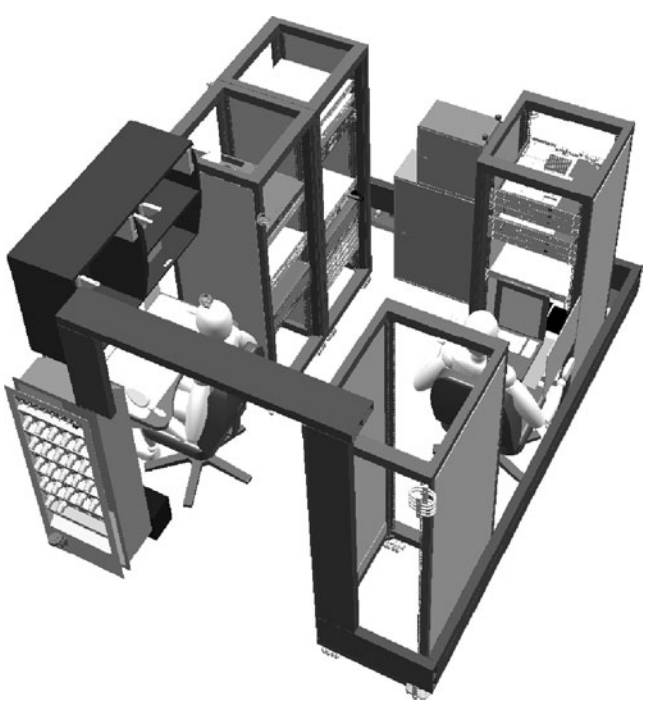

Fig. 3 Overall view of the shelter

Moreover, the space, represented by hatching in Fig. 4, is the space below the air-conditioner where no cabinet can be placed. This space is also a virtual component that is fixed during the optimization process

The dimensions of the shelter are 2150 mm × 2740 mm. The density of this configuration, without considering the spaces of accessibility of the different components, is equal to 50%. If the spaces of accessibility are considered, this density increases up to 90%.

3.2 Problem Formulation

Problem formulation is a very important step of the optimization process. The optimization problem studied here is an under constrained multi-objective problem. Let us see how the variables, constraints and design objectives are defined.

3.2.1 Optimization Variables

Each layout component has three optimization variables (X, Y, α): the coordinates of each element (a continued variable along X axis and another one along Y axis) and the rotation angle (one discreet variable along Z axis).

Consequently, the number of optimization variables for this problem is equal to $24(= 8\,\text{items} \times 3\,\text{coordinates})$. Because of the rotation of each component, variables X and Y are bounded according to the following relation (for the variable X_i for example):

$$\min(l_i, L_i) < X_i < l_{\text{sh}} - \min(l_i, L_i) \quad (5)$$

where l_{sh} represents the width of the shelter. Here, l_i is the dimension of the component along X axis (it does not have to be confused as the width of the component i).

3.2.2 Design Constraints

The design constraints of this layout problem are non-overlap constraints. They are divided in four categories, according to the following classification:

- Non-overlap constraints between components ($C1$).
- Non-overlap constraints between components and spaces of accessibility (dotted rectangle represented in Fig. 4) ($C2$).
- Non-protrusion constraints between components, spaces of accessibility and the shelter ($C3$).
- Non-overlap constraints between cabinets and the space below the air-conditioner (hatching represented in Fig. 4) ($C4$).

The rectangular shape of components simplifies the formulation of design constraints. Thus, the non-overlap constraint between the rectangles i and j is equal to the intersection area between the component i and j (in cm^2). This area has been defined in Eq. (4). Actually, the objective of the separation algorithm is defined as:

$$F = C1 + C2 + C3 + C4 \quad (6)$$

3.2.3 Design Objectives

In collaboration with the company experts of this specific problem, we have considered for this optimization problem the five following design objectives:

- To minimize the distance between the center of gravity of components and the geometrical center of the shelter, in order to balance the masses inside the shelter (O1).
- To maximize the distance between the cabinet 1 and the cabinets 2 and 3 and the electrical box 2, in order to limit interactions between energy and electric network (O2, O3, O4).
- To minimize the distance between the electrical box 2 and one of the shelter's walls, in order to establish a connection with exterior (O5).

The design objectives O2, O3, O4 and O5 are formulated by the distance between the centers of gravity of elements. For example, the distance d_{ij} between the components i and j is equal to:

$$d_{ij} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2} \quad (7)$$

where x and y are the coordinates of the centers of gravity of the items i and j.

Let us consider the coordinates of the center of gravity of all the elements which are placed in the shelter. These coordinates are equal to:

$$X_{\text{gra}} = \frac{\sum_{i=1}^{N} (x_i \times m_i)}{\sum_{i=1}^{N} m_i}, \quad Y_{\text{gra}} = \frac{\sum_{i=1}^{N} (y_i \times m_i)}{\sum_{i=1}^{N} m_i} \quad (8)$$

where N is equal to the number of elements which have a mass: the cabinets, the desks, the electrical boxes and the air-conditioners. Then, by considering Eq. (7), the objective 1 (O1) is computed.

More designer's knowledge could be incorporated in the layout problem formulation. It means for example, in the configuration design of the shelter studied in this chapter, the design objective O5 can be deleted and the degree of freedom of the electrical box 2 can be reduced, in order to force it to displace along one of the walls of the shelter. The designer's contribution for formulation should simplify the search of feasible solutions by reducing the number of possible solutions.

3.3 Results and Analysis

The resolution of this optimization problem has been firstly realized only with the multi-objective optimizer MOGA-II. The algorithm has been randomly initialized with a population of 240 designs. Most of these initial designs did not respect the non-overlap constraints because they have been randomly generated. Because of the great density of this layout problem, only one or two feasible configurations were computed for each simulation. A configuration is defined as:

Design j is a new configuration if it differs from the design i by at least one of the following criteria:

- One of the components of the layout has been displaced from at least Δ mm along one of the axis X or Y, (Δ is set to 500 mm in this application).
- One of the components has been rotated.
- The minimum difference between the objective values of the two designs is bigger than a limit, for example, fixed at 10 cm.

These results lead us to use the method proposed in this chapter in order to generate, with only one optimization simulation, a set of well distributed Pareto-optimal designs.

Thus, the results obtained for each step of the method are described here:

1. *Separation algorithm and first interaction with the designer*: the algorithm has been randomly initialized with designs that do not respect non-overlap constraints. Then, a set of 162 "feasible" (it means that respect design constraints) designs have been computed. This population then has been completed with 78 individuals randomly generated in order to create the first population (240 individuals) and to guarantee the diversity of the genetic algorithm.
2. *Multi-Objective Genetic Algorithm*: the algorithm has searched optimal solutions by considering the design constraints and all the objectives of the problem. Then, after a hundred generations, a set of 172 feasible configurations have been computed. Fourty one of these solutions are Pareto-optimal designs. Figure 5 shows three of these Pareto-optimal configurations and the initial solution. It's important to mention that this initial configuration is an intuitive solution which has been generated only by considering geometric aspects.
   The Pareto-optimal solutions, shown in Fig. 5, point out a problem that is present in all the solutions computed by the algorithm. In fact, Fig. 5 shows that, even though the design is a feasible configuration that respects all the design constraints, some facilities (for example facilities $n°2$, 4, 5, 8 in the first solution) are not accessible from the shelter's entry. It means that a design constraint or an objective is missing in the layout problem formulation, in order to characterize the accessibility to a facility from the shelter's entry.
   Consequently, the problem description has been changed and a free corridor, located in the middle of the shelter, has been added. In fact, this corridor is a space of living that can be considered as a fixed virtual component, where all the material components can not be placed. This space is going to resolve the problem of accessibility inside the shelter.
   Then, with the separation algorithm, a set of feasible designs have been computed and by interacting directly with them and by relaxing the design constraints (until 150 cm^2), the designer has selected 78 different designs. This population then has been completed with 162 individuals randomly generated. Next, the genetic algorithm has generated 14 feasible configurations whose 7 are Pareto-optimal solutions.
3. *Interactive decision making*: the 7 Pareto-optimal designs do not dominate the initial solution. On the other hand, the initial solution does not dominate either the solutions computed by the proposed method. Actually, it means that the designer is the only person who can make the final design choices.

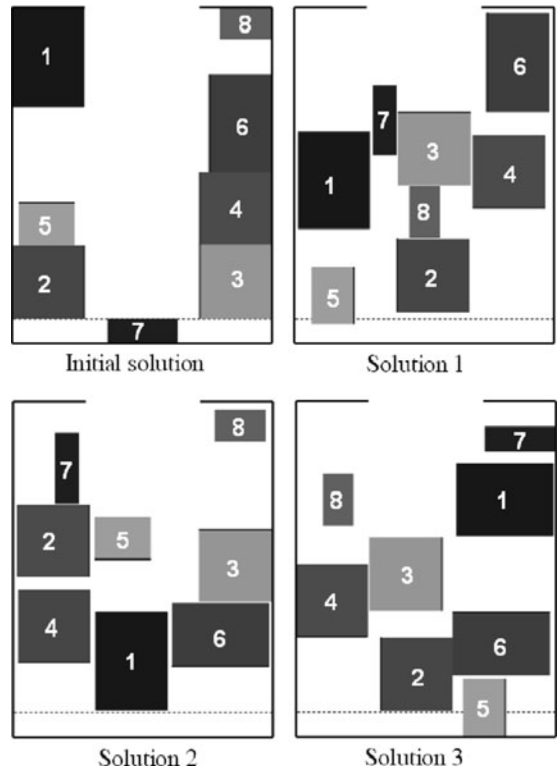

Fig. 5 Solution computed by the algorithm

In order to make a decision, the method provides to the designer an interactive geometric and numeric visualization of the designs. The designer can explore the set of non-dominated solutions, compare their objective values and interact with them. Figure 6 represents the interface that allows the designer to visualize at the same time the layout design and the associated design constraints and objectives values. The designer can also compare two solutions. In fact, when the designer displaces one component or changes its

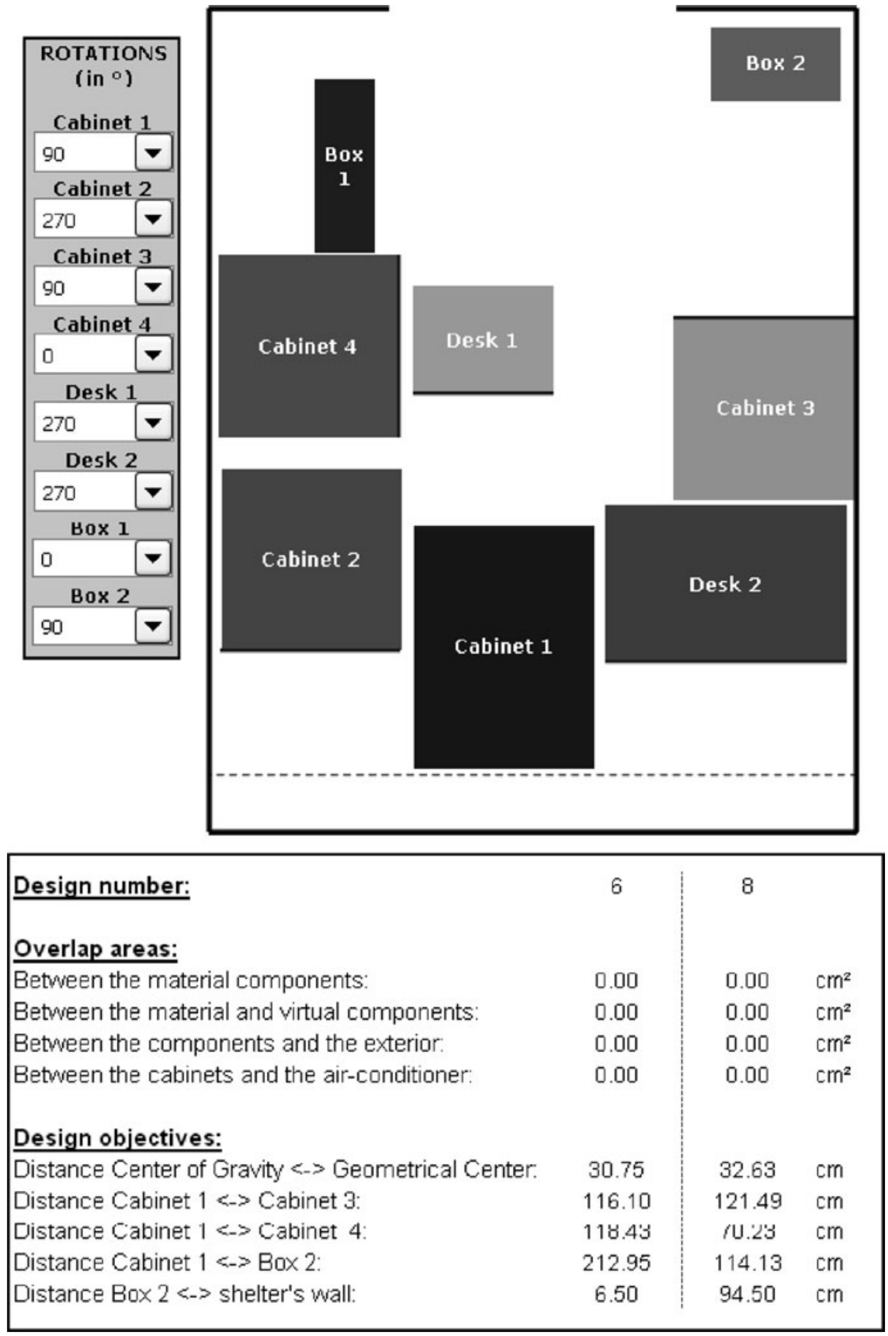

Fig. 6 Interactive layout interface

direction, the design constraints and objectives are automatically actualized.

Actually, among the 7 Pareto-optimal solutions computed by the algorithm, let us focus on the third solution. Locally changing the location of some components of this design improves its performances. Figure 7 shows this solution 3 and the solution that results from the modifications made by the designer.

Table 2 describes all the objectives values for the initial solution generated by the expert, the solution 3 and the solution 3 locally modified by the designer. Actually, due to the interaction of the designer with the final solutions, a new solution, better than the initial one, is created.

4 Retrospect and Perspective

This chapter has introduced a new interactive optimization strategy for solving layout problems. The method can be divided into several steps, as shown in Fig. 8. Firstly, a population of designs, randomly initialized, is optimized by the separation algorithm. Then, the designer interacts with the

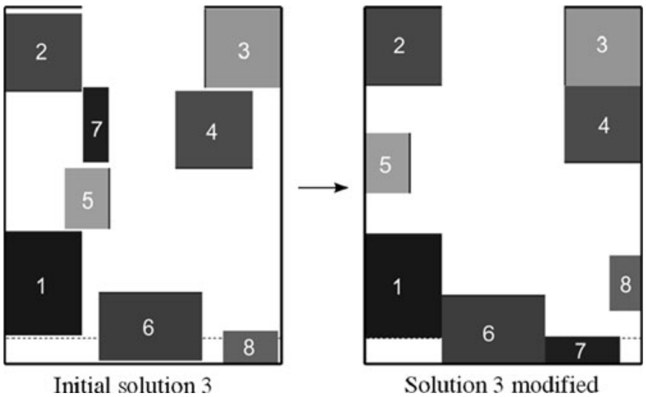

Fig. 7 Local modification of the solution 3

Table 2 Industrial solution vs. solution 3

Design objective	Initial solution (cm)	Solution 3 (cm)	Improved solution 3 (cm)
O1 (minimize)	25.41	8.67	3.48
O2 (maximize)	240.58	238.30	240.58
O3 (maximize)	198.50	177.80	198.50
O4 (maximize)	165.80	168.29	172.51
O5 (minimize)	0	0	0

solutions computed by the algorithm and selects some individuals according to the design constraints. Secondly, the new population is optimized by the multi-objective optimizer by considering all the design objectives. Then, the designer can locally modify some computed designs in order to improve their objectives. Actually, our strategy has the innovative particularity to allow the designer to interact with the optimization process in order to improve the performances of the Pareto-optimal designs and to keep a good diversity in computed solutions.

The application, which has been studied in this chapter, has an innovative problem formulation because it introduces the concept of space of accessibility, which can be considered as a virtual component of the layout design. Moreover, this application emphasizes the problem of accessibility to a facility from the container's entry. This problem has been resolved by inserting the user's knowledge in the problem description. Here, the designer decided to insert a free corridor in the shelter in order to keep a space of accessibility to all the components.

However, when the designer decides to insert his job knowledge in the problem formulation, he automatically influences the search of solutions realised by the algorithm. If he wants to find innovative solutions, he has to simplify the problem description and to adapt the design constraints and the objectives to his design preferences. For example, in the application studied in this chapter, the idea is to consider the accessibility to the facilities as a design constraint

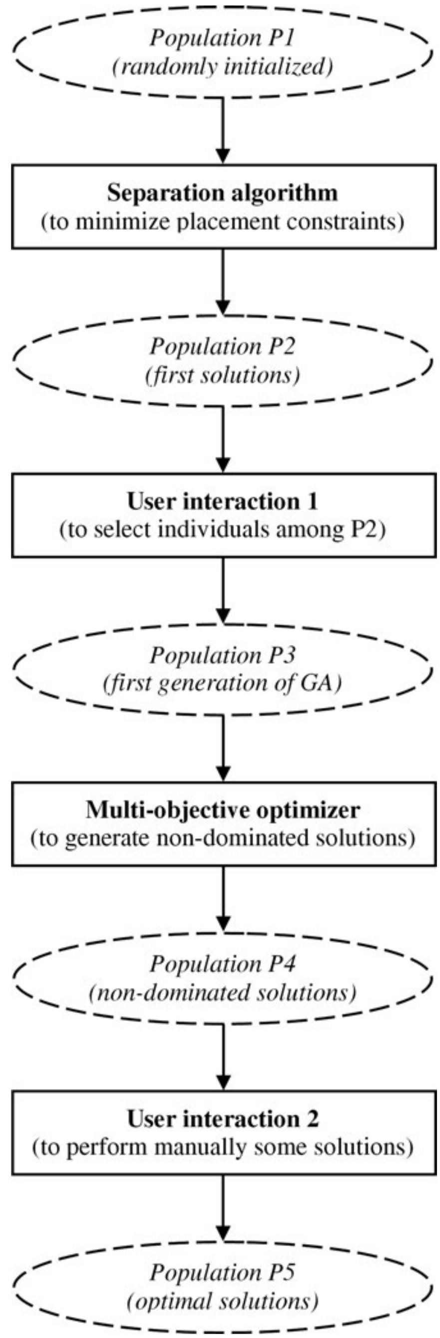

Fig. 8 Schematic representation of the optimization strategy

or an objective. Next research works have to explore this new concept.

Actually, this innovative optimization process proposed in this chapter also suggests that the method could be improved according to the designer preferences:

- Qualitative fitness could be inserted into design objectives. When solving complex design problems, as a layout problem for example, the translation of some constraints and objectives into simple mathematical expressions can be very difficult. It means that these constraints and objectives could be replaced by a mark given by designers in order to characterize their designs. Then, this qualitative fitness could be considered by the algorithm as a design objective. Alexandra Melike Brintrup et al. has already developed an interactive genetic algorithm-based framework for handling qualitative criteria in design optimization [14]. Actually, it should improve the performances of Pareto-optimal solutions.

- The designer could interact with design variables during the optimization process. Stopping the optimizer would allow the designer to firstly analyze a specific solution, secondly locally modify the design configuration and then decide to keep this modified design in the next generation of the genetic algorithm. We can find in [15] a significant contribution to this concept applied to the design optimization of architectural layouts.

5 Conclusion

This article presents an innovative layout problem formulation including the concept of space of accessibility defined in Sect. 3. It shows that problem formulation is a very important step in the optimization process because it has a great impact on computed solutions. Secondly, the hybridization of the separation algorithm and the multi-objective algorithm is a very efficient method to ensure a good diversity in a Pareto-optimal solutions set. Moreover, the strategy is designed to allow the interaction between the user and the optimization process in order to improve the performances of Pareto-optimal designs.

Actually, for industrial experts, design optimization has great advantages. On the one hand, it allows the designers to explore more alternative solutions to their problem. This is a very good way to encourage the innovation. On the other hand, using design optimization lets the designer to easily make his design choices and justifying them with quantitative values related to his problem formulation.

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A Case Study of Capitalisation and Valorisation of Our Technical Heritage

F. Laroche, J.-L. Kerouanton, and A. Bernard

Abstract For the 2008 CIRP Design conference, we have presented a scientific article dealing with a new way of thinking our technical heritage: we would like to preserve it as a digital object. Project deals with a physical mock-up of Nantes city built in 1899 and used for the Universal exposition in France in 1900 in Paris. The heritage object is nowadays in the museum but exposed as a fish inside an aquarium. Thanks to a virtual system coupling a tactile screen with semantic research modules, 3D active screen and light pointer, it will allow the visitor to better understand the mock-up and emphasize important places of Nantes city life. However it does not mean beautiful 3D animation with nice static rendering; indeed, we create virtual mock-ups which are dynamically operating. We use CAD software and engineering simulation tools. Nowadays the global methodology has been improved: it is named Advanced Industrial Archaeology. In this communication, we will detail a new experimentation done in partnership with a French museum: the Château des Ducs de Bretagne in France. This project deals with a physical mock-up of Nantes city built in 1899 and exposed in 1900 for the World Fair that took place in Paris, France. The heritage object is nowadays in the museum but exposed as "a fish inside an aquarium". Thanks to a virtual system coupling a tactile screen with semantic research modules, a 3D active screen and a light pointer, it will allow the visitor to better understand the mock-up and emphasize important places of the city. The mock-up represents our industrial heritage with old shipyards of Nantes.

Keywords Knowledge data base · Virtual reality · 3D digitalisation · Industrial heritage · Socio-economic · Museum · Nantes

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1 Introduction and Context

Industrial archaeology is one specialty of archaeology. This discipline also study material remaining from the past but it focus more specifically on industrial heritage as: mining equipment, metallurgical and manufacturing plants, road, bridges, tunnels, railways, marine, waterways, aeronautic. . . Industrial archaeology is born in England in year 1940 with the first studies of the industrial revolution. However the industrial heritage is not so widely known, indicating a latent disinterest of our society for our industry.

Since 2004, our research team works to establish a new discipline: Advanced Industrial Archaeology (AIA). The term "Advanced" is the same extension as used by mechanical domain when dealing, for example about "Advanced CAD" where it suggests the use of new kind of specialized software for creating more complex surface or parameterized parts. . .

For the CIRP General Assembly in 2007, we have made a communication about the impact of 3D numerical devices and environments when redesigning and valorising mechanical systems [1].

The main idea developed in this chapter deals with the use of virtual technologies for heritage. But, when we speak about heritage, there are not only architecture or castles as the architects Houdin and Dassault System have demonstrated it using Catia V5 for understanding the Cheops pyramid [2]. Indeed, objects studied by our research team belong to scientific and/or technical domains. Machines, industries and socio-economical context are also very important for a better understanding of our history. Our proposition consists in overturning the time axis of the design process generally used for developing contemporary technical products. That means that we begin at the end of machine lifetime and come back to the initial need that define why the technical object had been created.

This global process is the core of what we call Advanced Industrial Archaeology:

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1. First step is the digitalization of the physical object and the capitalization of the know-how learnt by studding the machine.
2. Next, thanks to virtual reality technologies, we can valorise this amount of knowledge.

Due to globalisation, the enterprises have to work in networks more and more diversified and geographically dispersed. To reach cost, quality and delay optimisation, enterprises implement new information and communication technologies. The mechanical SMEs adopted this logical, but, even if they are more flexible, they face difficulties in the information exchange and share.

Nowadays, the methodology to design an old technical object has been validated and experimented on several case studies: *capitalize formalize valorise.*

For this new edition of the CIRP Design, we would like to go further with the AIA adventure. We would like to demonstrate it also can be used to capitalize industrial sites and not only machines [3]. In this chapter, at first we will give basis about the general methodology where an information model will drives the heritage conservation process. Next, we will report a project started in September 2008, which should finished in 2011. It is done in partnership with the History Museum of Nantes (the Château des Ducs de Bretagne, department 44, France).

One specificity of this project and consequently one most difficulty is the fact that it is a pedagogical project. That means that students do all works. Indeed, it is one scientific hypothesis: we would like to renew the link between history, technique and culture. Then, efforts must be done for:

- Assuming prolongation of works,
- Having a global process overview,
- Allowing continuous knowledge.

Therefore, our students have written major part of the second part of this scientific article. It represents more than 12 teams; approximately 60 students since 2008. Consequently, they are all associated as co-authors for having participated in writing this chapter (see acknowledgements at the end).

2 Background: Scientific Basis

As described in our previous article in the CIRP Design conference [4], the AIA methodology of reverse engineering proposes 3 stages (Fig. 1).

One advantage of introducing the state B is to have the possibility of numerous finalities. In fact, going directly from state A to state C is not recommended. The various possibilities of final numerical product of state C (thesaurus virtual use for teaching or academic experts, reconstruction, museum valorisation. . .) show that it is necessary to capitalize a maximum amount of knowledge at the beginning of the heritage preservation project. Then, an intermediate structure containing all information, data and knowledge is required. It is a new virtual document that informs the heritage object. It is constituted of a virtual database allowing organising the knowledge involved. It is what we called the Digital Heritage Reference Model (DHRM).

This intermediate state B is more than a simple database. It must be able to support:

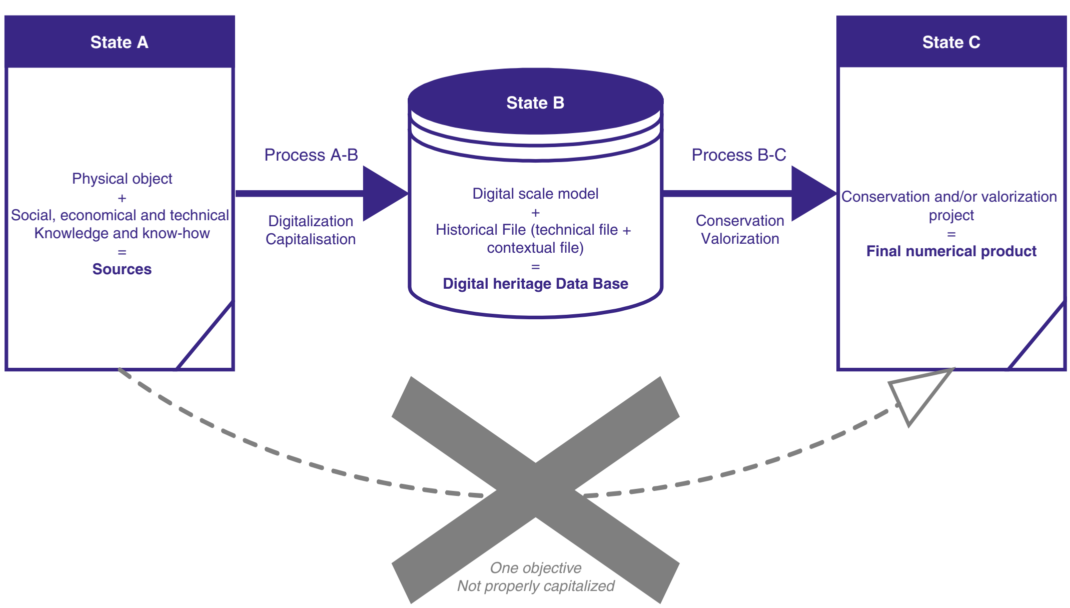

Fig. 1 General methodology to preserve and enhance the technical and industrial heritage

- past information of a specific object,
- contemporary information of the same object,
- relations between those two information past and present.

Last condition is very complicated to implement into a computer system. But, thanks to the use case detailed later in the article, new scientific hypotheses has been solved using a meta-model.

3 Information Model: Intermediary Representation of Design Model

Thus, we consider the heritage object studied as an object with several intermediate states. Evolution of those states is framed by a time axis unrolling the patrimonial process.

Figure 2 shows the four intermediary representation states and the three actions requires by the general methodology.

Indeed, all the intermediary objects use the same representation model. For each step of the digital heritage process, Fig. 3 shows:

- What have to be done (= action)
- Which state is the intermediary object
- What compound it (3D physical parts and/or documents)

Figure 4 gives an overview of the information system that drives the heritage process. The UML model details how the database can be constituted. This database is the main core of the DHRM. We can distinguish four steps as described below.

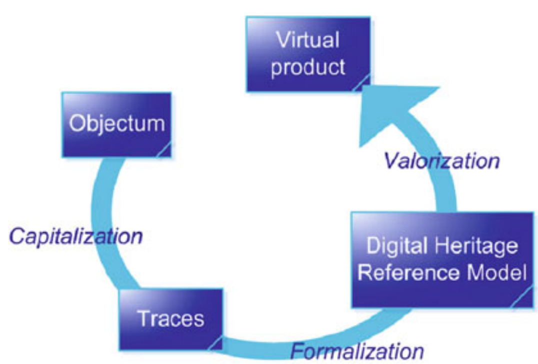

Fig. 2 Object transformation: different intermediary states

3.1 The "Objectum"

Why this object is beautiful? Why we like it? Why we do not like it? "Objectum" is the starting point of the heritage process. Indeed, when an object is going to disappear, many people are desperate to save it. What is the purpose? No answer can be provided and no one knows how to explain it but everyone agrees that the object must be preserved. Indeed, it is a feeling; it gives us emotion. The dictionary would say: "Objectum is something that affects senses". According to UNESCO point of view, an object must be conserved if it has:

- an aesthetic value
- an historical value
- and so it has an exceptional significance at the world level

3.2 The "Traces" of the Object

- "Traces". First step concerns data acquisition. We have to capture all physical information of the studied object and to capitalize all knowledge and know-how: socio-economic, technical and industry context... it is what we call a "trace". We can use Knowledge Management methods and tools that are commonly used by contemporary enterprises [5].
- "Vestiges". As sometimes the object falls done, it remains only "pieces" that compound "vestiges". For acquiring "vestiges", we can use for example callipers. Moreover, 3D scanning tools can sometimes be used in order to have more information, to capture more complex surfaces or if we are in a hurry of an object that is going to disappear or to be destroyed [6].

	Step	Action	State	Concetpual object manipulated	
0			Objectum	Vestiges	Records
1	Capitalization / Acquisition	Industrial Archaeology	Traces	Pieces	Sources
2	InterprEtation / Formalization / Design / Storage	Advanced Industrial Archaeology	Digital Heritage Reference Model	Digital Mock-up	Knowledge
3	Exploitation / Valorization	Final digital product for valorization	Virtual Product	Artifact	Hypertext

Fig. 3 Items handled during the digital heritage process

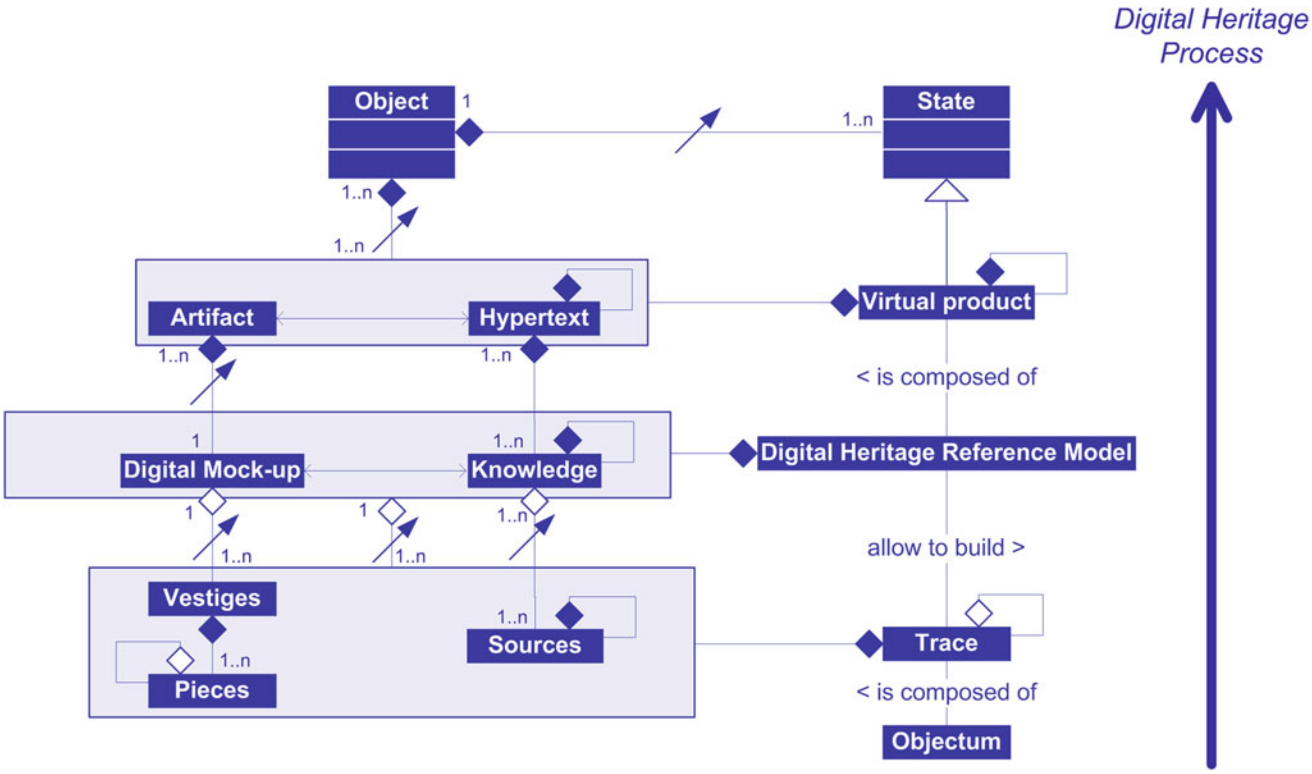

Fig. 4 Ontology describing conceptual objects manipulated

3.3 The Digital Heritage Reference Model

- "Knowledge". Implicit and explicit data have been collected; it is now necessary to organize, study and interconnect them. Consequently, there is a transformation of the sub-class "sources" into a new UML class of equivalence: "knowledge".
- "Digital mock-up". The technical understanding phase allow using the 3D data. Main objective consists in designing a complete 3D digital model. In order to have a precise model, we use engineering software tools probing that the model are scientifically realistic [7]. However, 3D scan is not enough for the global comprehension and the object must be contextualized. External knowledge and anthropological investigations are therefore correlated with the 3D cloud of points and, at the end of the study; an operating digital mock-up is designed. Then "sources" allow validating the DMU (= Digital Mock-Up).

3.4 Virtual Product for Museum Valorisation

- "Artifact". The term is widely used by museum curators. It is one representation of the object. It can be one part of the object, as sometimes the original object does not exist in its original condition.
- "Hypertext". This conceptual class explains the surrounding of the object. It allows giving back the accumulated data and knowledge produced. In a museum, the hypertext will replace the labels put near an object for explaining it. But as labels must be no longer than 50 words, it is a real difficulty to choose if we put a simple caption, a description of the subject, or tell a story…? It is so restrictive of the amount of knowledge accumulated that digital way will be the solution. It available to access the entire corpus description of the object.

4 Nantes1900 Project Experimentation

Thanks to the scientific work explained before we are developing a project in partnership with the Museum of Nantes in France. One of the objectives consists to create the Digital Heritage Reference Model for the Museum. As it is an experience, if it succeeds, we hope to extend our proposition to numerous museums and also to propose it to French culture ministry in order to use it as the new reference model for capitalizing our heritage.

Notice that every student teams of the project have written following paragraphs of this communication. We have made some links between the different parts but no more in order to keep their original texts. Please, accept our excuses if you meet big mistakes.

4.1 *Context of the Project and Definition of the Heritage Object Studied*

Since the beginning, the city of Nantes (France) has always been a powerful harbour of the Atlantic sea. In order to demonstrate its power, the Chamber of Commerce of the city decided to order a mock-up of the harbour. It was established for the "World Fair Exposition" of 1900 in Paris. Later, it has been updated until the First World War. After the conflict, the Chamber of Commerce gave it to the Nantes City Museum (the Museum of Salorges). Nowadays, it is classified as a heritage object of the municipal collections. It is installed in the permanent exhibition of the Musée du Château des Ducs de Bretagne (Fig. 5).

The mock-up measures 9.2 m long and 1.85 m large. Paul Duchesne has built it in 1899. The scale is 1/450 (so as to have a comparison reference: streetlights stick have a diameter of 1 mm inside the mock-up). The full mock-up represents approximately 3.44 km^2 of Nantes city harbour. Recently, the Museum decided that this Nantes harbour mock-up must "speak". Thus, a partnership was established between the museum and Nantes school institutions (Ecole Centrale, University…) in order to model it and propose an innovative form of valorisation.

The digital modelling of this mock-up allows historical analysis of the industrial situation at the beginning of the 20th century. For example, the harbour can be considered as a prolongation of the old city. Beyond of a simple "photography" in three dimensions done by 3D scanners, there is a real problematic of interoperability between topographic data and documentary information. This knowledge can help to understand the circulation and exchange flows of the industrial landscape [8] (Fig. 6).

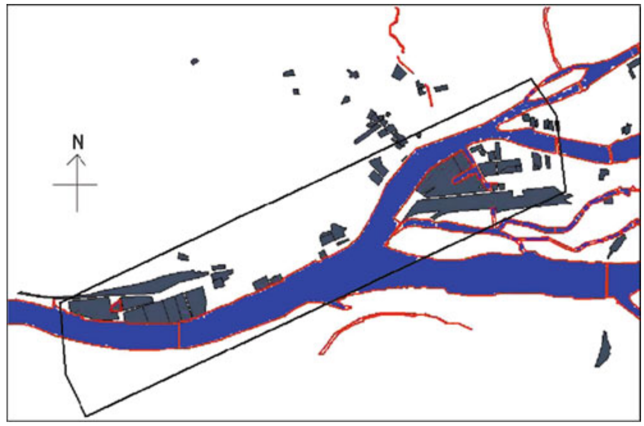

Fig. 6 Borders of the mock-up on a SIG map

4.2 *Objectives and Main Steps: Innovation as a Keyword!*

The project purpose is to develop an interactive system between the visitor, the Internet, the physical model and the database associated to the virtual representation of the heritage object. The public presentation should be innovative, easy to use and educational. The device will allow combining an Augmented Reality system inside the museum room so that every visitor can access the knowledge (it is an in vivo system). Moreover, the system will allow valorising the accumulation of historical knowledge for a wide distribution, access to libraries or on the Internet; mainly targeted to students and researchers (Fig. 7).

Fig. 5 The physical mock-up inside its "aquarium"

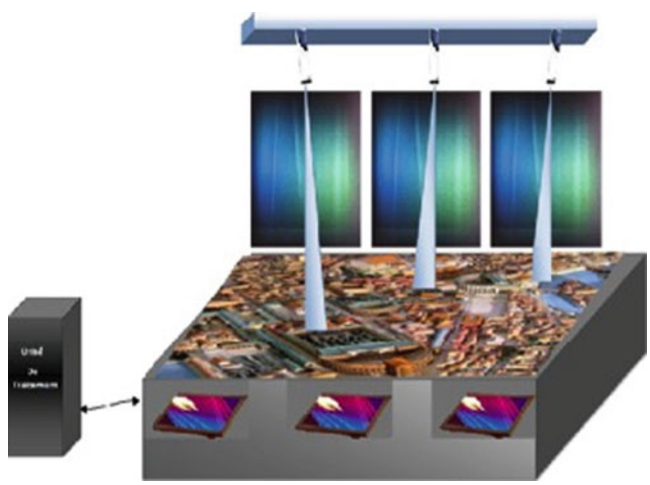

Fig. 7 Illustration of the future virtual reality system

Main aspect concerns the creation of the Digital Heritage Reference Model database that will support the knowledge. It will include a 3D scanned model and a compilation of the artefact' knowledge. The data management system will support heterogeneous format (text, image, sound, videos. . .) and will propose a semantic indexer/researcher.

4.3 Museum Constraints: Multimedia/Opensource

Notice that one most important constraint is that the system will be Open source (Museum technology choice) in order to permit evolution and upgrade of the knowledge base. Our project will also respect the museum policy: valorising heritage collections by NTIC media. Educational and fun as the same time, those facilities enrich and enlighten the museum and can reach a wider audience.

16 kiosks and over 24 broadcast stations, archives, sound clips, movies (including real-time 3D reconstruction of Nantes in 1756), and 180° immersive projection have been selected and developed by the Museum. Nantes1900 project is a new one that will continue efforts done until nowadays. An operating prototype will be delivered and tested inside the museum in July 2010 (Fig. 8).

4.4 Inter-Disciplinarity Competencies: A University Project

This project is a multi-field and transversal experiment requiring numerous competences:

- Social and human sciences for the technical and industrial history, memories & heritage, geographical analyses, heritage and museography. . .
- Engineering sciences for 3D scanning, mechanical design, mathematical computation, informatics database, virtual reality development. . .

Notice that the mechanical team works on the DMU (Digital Mock-Up). After the digitalization, they are trying to automate the 3D mesh simplification and the colorization of the cloud of points.

Due to the duality between engineering domain and social domain, Nantes1900 project is a new challenge: team is heterogeneous in terms of vocabulary, method of work, issue or area of expertise. . .

One more originality of the project lies to its composition: all members are students from multiple universities and schools of Nantes. It is a voluntary choice done by the steering committee. This innovative approach has led the project to a lack of precise specifications; objective is to unleash the imagination and increase the creativity of the team. Consequently, obtained results are really original and would perhaps have never been found in other circumstances, for example by professionals specialized in museographic business!

Consequently the museum will enrich its know-how; and the students are offered the possibility practicing academic achievement thanks to a real and ambitious project. So as to succeed the project, an active collaboration has been initiated between the Ecole Centrale de Nantes, Ecole Polytechnique de Nantes and the University of Nantes (Department history/art history). This melting was facilitated by the presence of teachers shared between those different domains as shown by Fig. 9. Moreover, notice that all teachers belong to various Nantes laboratories that are complementary (IRCCyN, CFV, LINA, IRSTV, CERMA. . .)

Nantes1900 project uses a collaborative platform for working (Team Work Place of Lotus). This tool, connected to a server, allows everyone to access documents uploaded by other members. Team Work Place also includes a manager planning to facilitate the establishment of meetings and

Fig. 8 The Chateau des Ducs de Bretagne

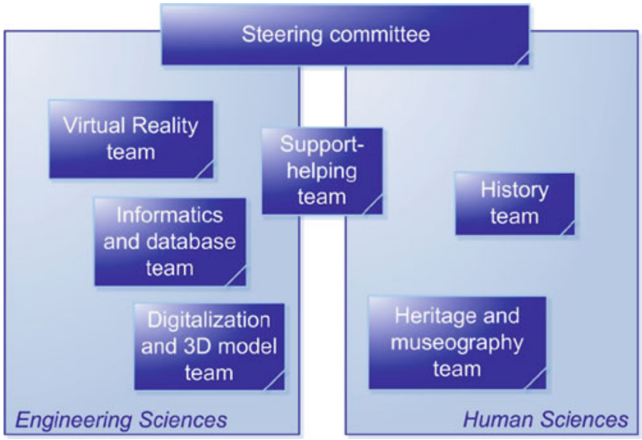

Fig. 9 Simplified organisation of Nantes1900 project

Fig. 10 3D digitalisation inside the museum

main steps of the project. Finally, the use of a collaborative virtual tool provides full traceability of the process in order to capitalize on this experience.

The project is divided into several phases. Each team is involved into one or more tasks. Below are summaries of each task done by students. Notice that they emphasize skills used and acquired.

4.4.1 3D Digitalization and Mock-up

Objectives

Take a 3D picture of the physical mock-up in order to "immortalize" it. Indeed, there were many objectives to make a 3D digitalization of the heritage object:

- To preserve it as a virtual copy in case of a potential damage,
- To become a new artefact (see first part of this chapter about intermediary representation object) that will be used by professionals of heritage domain; such as historian that can study the object directly on their laptop
- To be an intermediary representation and to capture 3D information in case of a 3D design into a virtual world

Moreover, as it was impossible to move the physical mock-up or to close the museum room, the challenge was to realize the 3D digitalization inside the museum with the public. As it is a pedagogical project, it was another objective to let the visitor discover new technologies and how students manipulate it. For seeing them in action, look at the television reports by taping the keyword "nantes1900" in www.dailymotion.com

Method

We use a new technology: the Handyscan from the Company Creaform (www.creaform3d.com). Based on a Canadian patent, this tool allows digitalizing an object for obtaining a cloud of points. The scanner is self-positioned in 3D space thanks to reflecting targets. It is possible to scan many times the same point for optimizing its position. This technique is without contact and cannot destroy the object, as the laser emitted is visible by human. Moreover, we had the constraint that turning around or going above it was very difficult. Consequently, as Handyscan is handled, it allows user to position it where he wants (Fig. 10).

Deliverable and Assessment

- 2 scanners used
- 23 days
- Approximately 3 persons per day
- 174 sessions of STL files
- 4000 photography's for informing cloud of points
- 96,000,000 points
- 2/3 of the mock-up has been digitalized (as scanner have crashed); new step will begin in June 2010 (Fig. 11)

Considering that the mock-up is at the scale 1/500 it means that a human measures approximately 3 mm inside the physical mock-up. Notice that the precision is 0.53 mm; that means the virtual model contains one point each 265 mm. Such resolution is said incredible by mathematician or geographical people specialized in GIS (Geographical Information System). Indeed, that means that we obtain a 3D model at 26 cm precision but at the scale of a city! (Fig. 12).

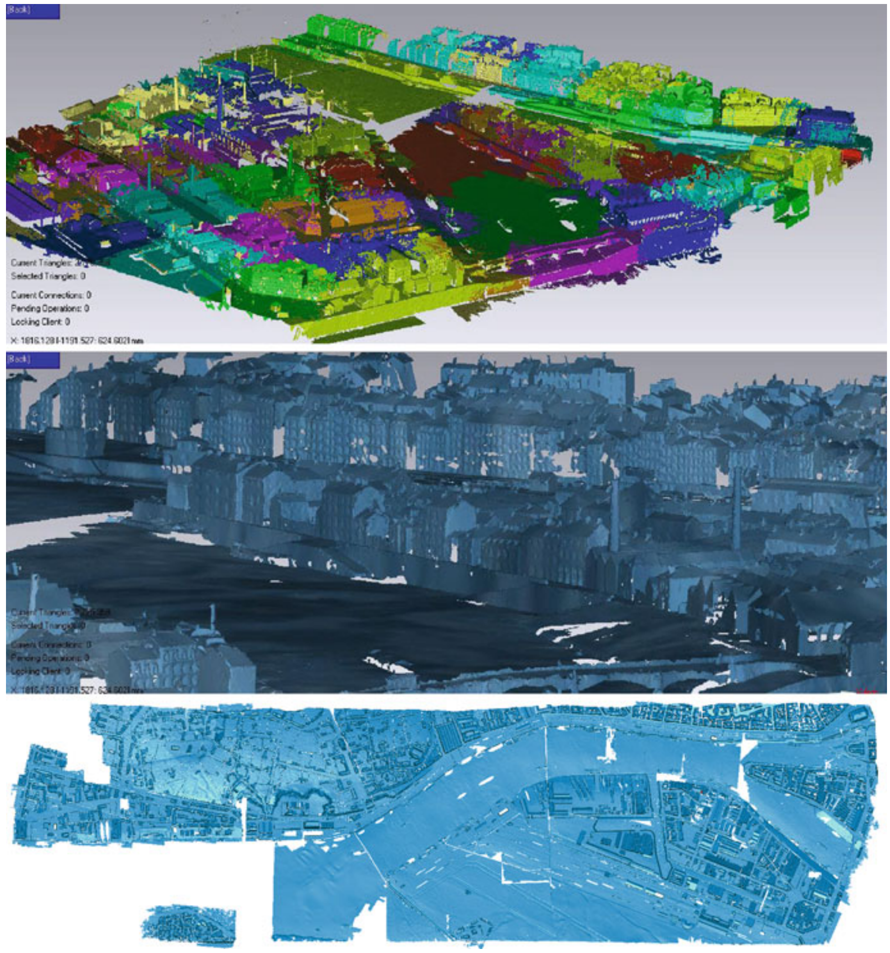

Fig. 11 Extract view of the 3D digitalisation

Fig. 12 Slide callipers demonstrating the littlest of the mock-up

Colorization/Texturing a Cloud of Points

After the digitalisation, we have only the cloud of points, without any colour. To improve the reality of the digitalized model, we had to put some colours or textures on it. After a big state of the art, we decided to try our own method: use the normal of the points for colorizing (Fig. 13).

Indeed, the ground has vertical normal, wall horizontal normal and other vertical by default are roof. Firstly, we segmented the cloud of points with an algorithm similar to Rabbani et al. [15], in many plans, considering that wall, roof and ground have similar normals. Moreover, with a building model, we can have specifics characteristics and thus we used Pu and Vosselman method [10]. It allows fractionise the town into buildings, and each building into roof, ground and wall. With this method, we have a first realistic view of a coloured model. Moreover, this segmentation can help historians to better understand the model and search specific information's.

4.4.2 3D Mesh Simplification

General Objectives

Files obtained by the digitalisation cannot be manipulated in an easy way as they are too heavy. Indeed, the entire file is constituted of 96 million points and there is no current system able to open it and to make a preview. That's objective of

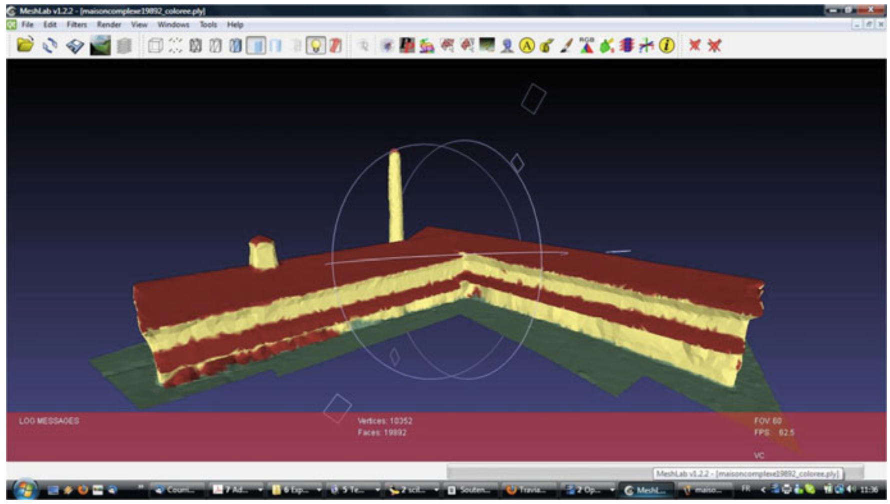

Fig. 13 First experimentation of 3D colorization

this team is to develop a method and a tool for decimating automatically numerous scanned files (Fig. 14).

Deliverables

We had obtained a decimation method for 3D files and we have programmed it in C++; it can also be implemented in OpenMesh. Moreover we simplify the 3D model to a 2D vectorized model that can be used in GIS (Geographical Information System).

Personal Profits

Belonging to informatics' domain, this project allows us to discover heritage and museographic domains. Work on new technologies as digitalization. Learning how to structure and manipulate 3D data. Project management in autonomy and in connection with the other teams project.

4.4.3 History Team

General Objective

The purpose of the group History/Heritage in Nantes 1900 project is to document the artefact and thus "feed" the database. This is the common work of historians (records and literature researches).

Deliverables

The team had two forms of deliverables: firstly, the documentation of the model and its database thanks to studies of heritage records. This work is like a picture of the mock-up with thousand references. Secondly, it was not really a deliverable but more a support to other groups: for improving understanding between the two worlds: the technicians and historians (understand the relationship between an historian, a scientific history subject, a curator, a visitor and the enhancement tool).

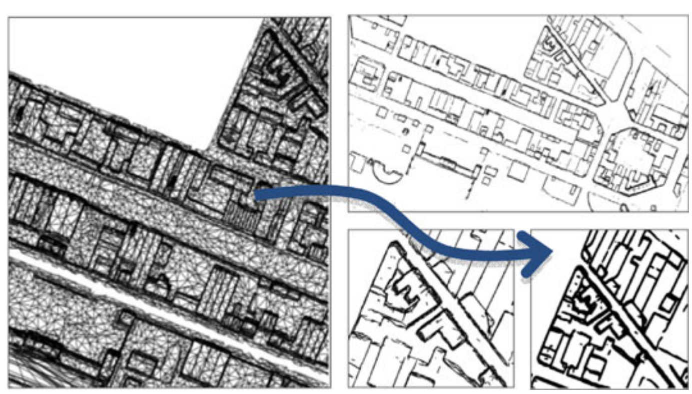

Fig. 14 3D decimation: 5% reduction to 2D file

Skills Acquired

During the project, the history team has learned a lot especially in terms of confrontation with members from technology domains. The meeting between those two worlds has been particularly enriching. The project was an opportunity to familiarize historians with the construction of database, 3D scanning with a handheld scanner. . .

Personal Benefits

The Nantes1900 project was an opportunity to participate in a scientific research project and advanced technology gathering partners from different fields of study. In addition, this project was aimed at a famous museum, especially facing the use of new technologies for cultural mediation (Fig. 15).

4.4.4 Informatics and Database Team

Aims

Create a scalable database storing the geo-localized 3D model and a big amount of indexed heterogeneous documents. Moreover, we have to develop a search engine linked to the content of the database. So as to, a UML model has been developed. It is an operating view of the DHRM. First of all a state of the art of similar project have been done. Many heritage database have been found about digital libraries, digital humanities [11] as Gallica, CNUM, Mérimée. . . with associated projects as Rome reborn [12–15], Prague mock-up [16]. . . The powerful of our model is that it is "intelligent" as it will automatically create and adapt its structure when new categories of elements will be entered (by non informatics' people) (Fig. 16).

Fig. 15 Historical records: Nantes Harbour in 1900

Deliverable

In addition to a fully functional database, the team will provide a web interface (for tests only).

Interfacing with Other Teams

Main difficulty deals with the ability to provide an interface allowing two independent teams to execute search query (light pointing devices team and multi-touch screen team). Thus, through using localized coordinates from the model, the system returns a list of answers sorted by relevance and split into several categories (main topic, photos, related topics, close places. . .). Moreover, system will be "intelligent": queries must use semantic entries and not keywords (Fig. 17).

Skills and Personal Benefits

This project represents for our informatics' team an incredible opportunity to contribute to a great museum project. The discussions between historians and computer scientists taught students to adapt their speech in order to be understood by everyone. This project is a real opportunity for students to work with very different kinds of people and to put the knowledge we learned at school into practice.

4.4.5 Virtual Reality Application

General Objectives

This team is in charge to develop an interactive pointing device coupled to a tactile screen and a 3D stereoscopic screen. One of the success keys consists to achieve a pointing device allowing to link the physical object and its digital representation. Visitors will be able to see the virtual view thanks to interactive terminals as show by Fig. 18.

Deliverable

It will be a prototype of an operating pointing device. This prototype will be constituted of a projector light dimensioned according to the constraint of the non-destruction of the physical mock-up. Developed software will control the projector thanks to an electronic interface.

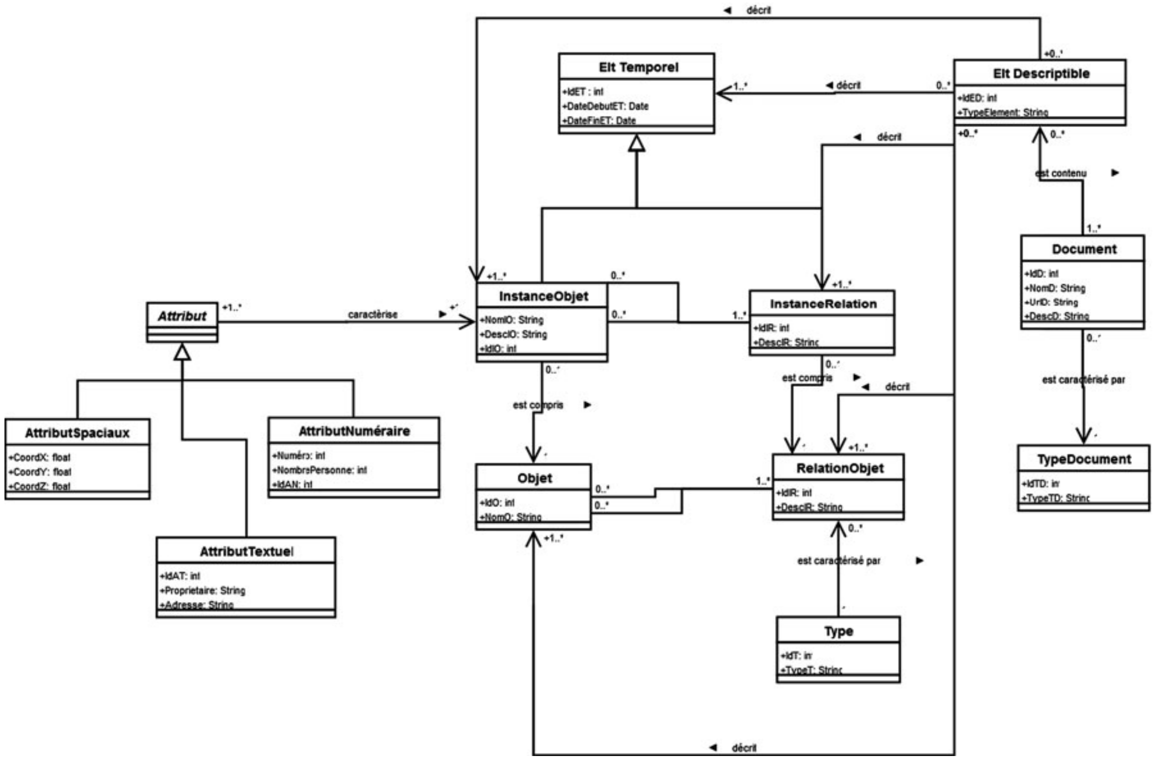

Fig. 16 DHRM model for the Nantes1900 project database

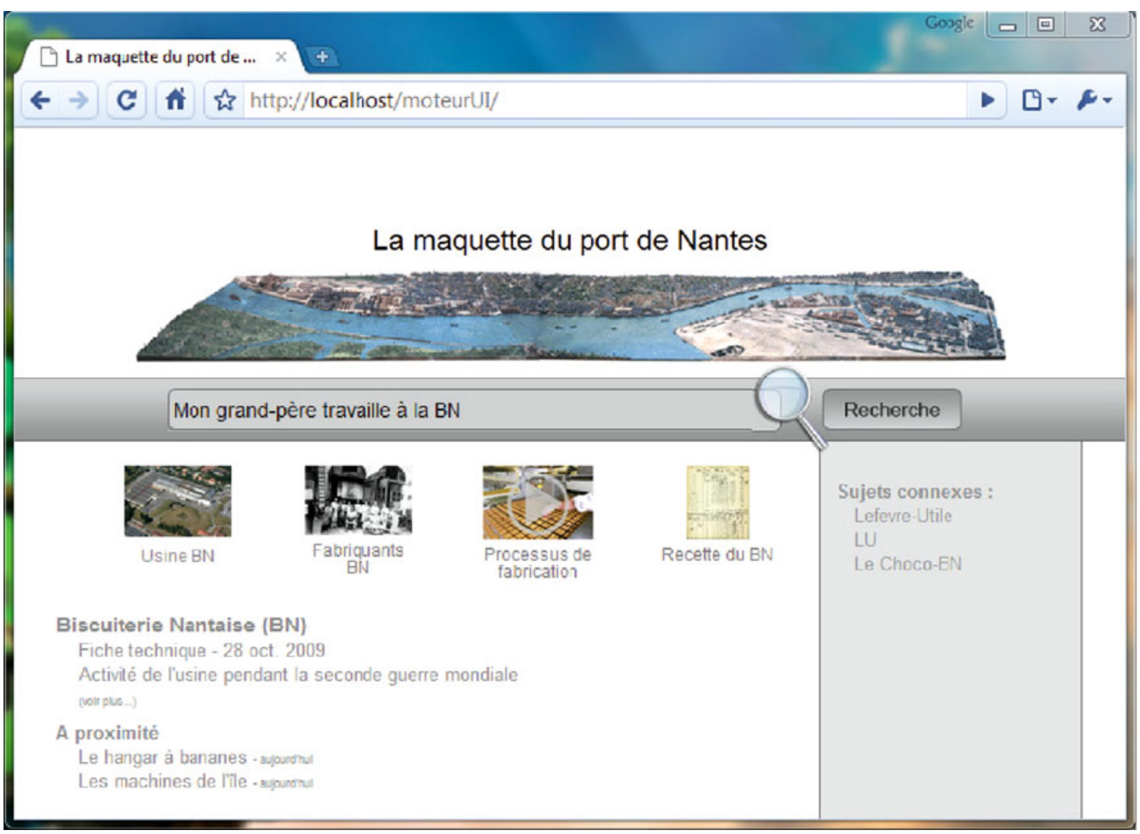

Fig. 17 First results of the semantic search engine

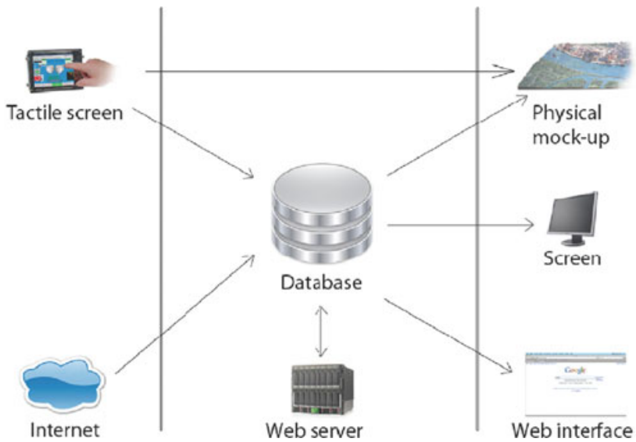

Fig. 18 Functional diagram

Interfacing with Other Teams

The pointing device must be able to retrieve and process data location to a light point on the physical mock-up. Obviously queries done by visitors on the tactile screen will also returns results directly on the same tactile screen. In addition, the 3D screen placed in front of the visitor will give him more information as for example a 3D sketch or the 3D cloud points of the buildings or blocks he is studying.

Personal Benefits

Working with people with training and owning varied experiences is very rich. Further work on a subject of such history allows students to learn more about the history of Nantes .

4.5 Conclusion

One of the particularities of Nantes1900 project is linked to its strong interdisciplinary.

As a conclusion, we can say that at the beginning of the project there is only an old object aged more than 100 years old. But more than 60 persons among students, teachers, researchers and professionals have been and are still working for this study.

Obviously they are not only students from engineering schools or historical department; sooner, students in geography will join them. The Nantes1900 project requires several domain of excellence. Each student brings the methods and practices of his expertise and its specific knowledge. This is the basis for interdisciplinary. Interdisciplinary facilitates discovery of other university courses offered in Nantes.

Interdisciplinary also results in comparing the different methodologies from involved disciplines. Most of the time processes are different. Indeed, interdisciplinary create a synergy which is very beneficial and indispensable for succeeding the project. Various fields took alone could not drive it; mixing new disciplines is a new kind of design process where keywords are not power but culture and knowledge.

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- Jean-Louis Kerouanton – teacher-researcher University of Nantes, UFR Sciences et Techniques and member of the laboratory Centre Francois Viète (EA CNRS 1161),
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A Design Logistics Support Tool on an Operational Level

L. Louis-sidney, V. Cheutet, S. Lamouri, O. Puron, and A. Mezza

Abstract The level of efficiency in the dissemination of knowledge within an organization is recognized as being a competitive advantage. Therefore, various means appeared in order to share it. Among the existing ways, the use of documents and files to encapsulated consistent knowledge of refined granularity (figures, words, etc.) is a well-known practice. However, the latter sometimes complicates its extraction or reuse in product re-development project. For a large company, improvement resides in the need to implement veritable design logistics covering also this knowledge of refined granularity. The purpose of this chapter is to propose a solution to support the automated sharing of this type of knowledge in the context of a product design process. This solution is based on an information system, the architecture of which will be presented and partially validated by the implementation of an application case provided by our industrial partner, Renault-DIM (Mechanical Engineering Department).

Keywords Knowledge · Granularity · Exchange · Information system · Design process

1 Introduction

In a large industrial company, the success of a product design project is partly based on the sharing of knowledge [1] which takes place on two levels:

- between previous and current project teams,
- between the members of a project team.

The scientific issue associated with the first level of sharing mentioned is knowledge capitalisation. The objectives here are to be able to locate, actualize, enhance, preserve and manage knowledge [2]. The information systems defined to meet this need are termed knowledge management systems [3]. However, the latter have a certain number of limitations. A recent practical study conducted by Joo and Lee [4] has endeavoured to describe the causes of user dissatisfaction with this type of tool. In particular, two major causes can be found: difficulty with their knowledge base searches and lack of integration of the latter with other systems. This observation also applies at Renault-DIM, our industrial partner for this work. The members of a project team finding themselves facing two fastidious tasks in the search for and recopying of a mass of knowledge. In this context, knowledge management systems do not offer adequate facility of use and, as a result, do not foster integration of the knowledge formally expressed in the product design process.

PDM (Product Data Management) tools are used to handle the second level of sharing: they constitute information systems the aim of which is to ensure integrity of the product data defined during the project [5]. However, this data mainly corresponds to files considered as being black boxes. Pikosz [6] underscores this limit of PDMs that only manage documents via metadata and cannot access the knowledge they encapsulate. This knowledge, of a more refined level of granularity than that of a file, is therefore outside the scope of control.

Consequently, reference knowledge sharing tools (compared with collaboration resources on a much less official level such as e-mail, telephone, etc.) do not enable optimum dissemination of the latter when defined with a refined level of granularity (e.g. value of a geometric dimension or tolerance). The issue at stake here is to propose an information system dedicated to design logistics [1]: a function aimed at the control and optimisation of knowledge flows in design. It will enable the management of knowledgesharing,

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irrespective of whether the knowledge has been acquired from capitalisation or defined in the course of the project.

The remainder of this chapter is organised as follows: the second section is devoted to analysis of the issue at stake with the proposal of architecture for the information in the third section. Finally, we will cover the first tests conducted on the basis of this architecture by means of an industrial case study.

2 Modelling and Knowledge Sharing

2.1 *Knowledge*

In [1] we gave the definitions we have assigned to the notions of information and knowledge. Information corresponds to any data likely to take on a particular meaning for an individual. Information is transformed into knowledge when an individual understands its necessity for an activity. We would like to specify here the definition that we give to data: it is an elementary entity without semantics attributed to it. We will give here the example proposed in [1] to clarify our statement:

- "10/12/09" is "data",
- "10/12/09", associated with the notion of "date" is information,
- "10/12/09", associated with the notion of "date" used in the context of "validation of the drawing of Part N°xxx following correction" is knowledge.

In this section, we will discuss modelling and knowledge sharing since we are positioning ourselves from the standpoint of the information system owner requiring the data to be perceived as such.

The kinds of typology of the refined granularity knowledge to be shared during a design process are numerous (dimension of a part, flatness of a surface, materials, etc.). A study of CAD (Computer-Assisted Design) tools is particularly interesting to obtain an initial idea of these kinds of typology as they are at the core of the specification of the final product (drawing and 3D model). Nowadays, via the parameterisation of the model, they enable design logic to be integrated. The parameters therefore reflect the user knowledge to be integrated into the CAD model. However, the modelling chosen by publishers is not unique. Pratt et al. have shown the difficulties brought about by this situation in terms of the exchange of parameterised models between CAD applications [7]. In this, they proposed an upgrade to ISO AP203 to satisfy this requirement. While awaiting this new version, this work has recently been continued by Kim [8] resulting in a non-exclusive classification of the parameters handled by CAD applications:

- numerical vs. non-numerical,
- with boundaries vs. without boundaries,
- dimensional vs. non-dimensional,
- explicit vs. implicit: a parameter is explicit when a user uses a command to create it. A parameter is implicit when it is automatically created by the instantiation of a feature of which it is an attribute (potentially variable),
- dependent vs. independent vs. unrestricted: a parameter is termed dependent when its value is governed by a constraint. It is independent when its value can be edited and can govern the value of another parameter via a constraint. It is unrestricted when it is not involved in a constraint.

This classification consists of: criteria inherent in the CAD application (explicit vs. implicit), criteria of a semantic nature, giving meaning to data (dimensional vs. non dimensional), criteria of a qualificative nature characterising the data (numerical vs. non-numerical, with boundaries vs. without boundaries) and criteria relative to the position of a parameter within a network of parameters (dependent vs. independent vs. unrestricted). The latter criterion relates to the notion of network of knowledge developed further on in this section.

The modelling of knowledge taking place in our information system should integrate all the criteria selected above, except those inherent in the CAD application (the latter are of no interest for this modelling, the aim of which is to obtain a unique referential dedicated to knowledge sharing). It will enable a dictionary to be set up, capitalising on the semantics associated with the data. This dictionary will refer to the occasion of an exchange of knowledge.

2.2 *The Network of Knowledge*

The interlinking of knowledge is of capital importance for its use. In his approach to knowledge management via knowledge engineering Lai [9] mentions that knowledge management systems lack analysis and reasoning functions. He suggests the use of Sowa's conceptual graphs to interlink knowledge. However, his work is principally focussed on knowledge that we could term as "static": a set of permanent knowledge encapsulated in a use context. He thus models all the tasks to be accomplished to verify the correct operation of an LCD screen. Our industrial work environment means that we must have a more dynamic approach to knowledge which is refined during the course of a project. As in many manufacturing companies, at Renault-DIM, most projects are redesign projects. While we are immutably aware that the technological solution chosen for the assembly of a given

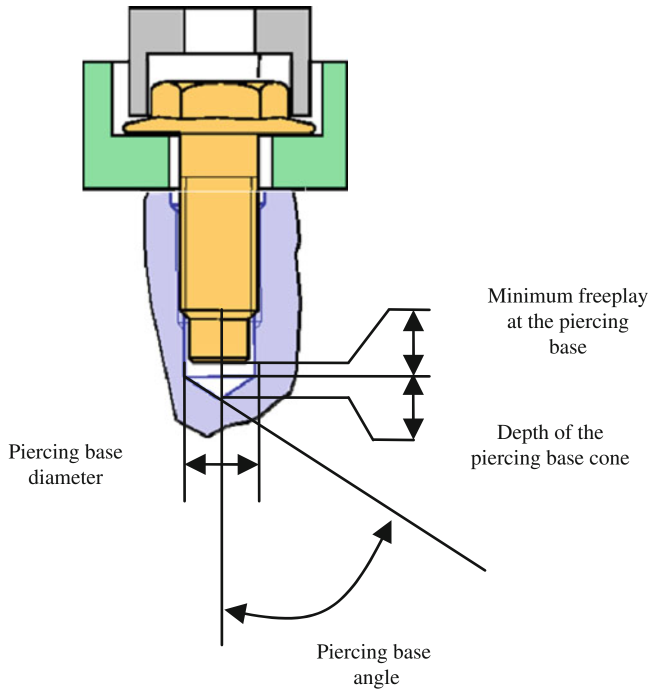

Fig. 1 Diagram of a screwed assembly

part onto a given bracket will be a screwed assembly, we often still have to optimise the components (screw, flange zone concerned, the bracket zone concerned). This optimisation is undertaken in such a manner as to satisfy the functional criteria (length of screw thread engaged, elastic length, etc.) as well as minimise the resulting costs. Thus, from a functional standpoint, keeping to the minimum freeplay at the foot of the piercing base will enable the depth of the piercing base cone to be adjusted (Fig. 1) andthe torque chosen from a standard selection enabling assembly costs to be reduced, will determine the diameter of the screw. However, knowledge of the diameter of a screw is totally linked to knowledge of the diameter of the threaded shank and the depth of the piercing base cone can be deduced from the piercing base diameter and the piercing base angle (Fig. 1). Without blocking the knowledge life cycle or making it complex, we then need to take into account the relations that link the pieces of knowledge in order to ensure consistency when shared.

The classification of CAD parameters proposed above by Kim [8] has already enabled "dependent", "interdependent" and "unrestricted" parameters to be demonstrated. We will retain this terminology and related definitions to describe knowledge in the remainder of this chapter. Our industrial working context has enabled us to determine two kinds of link typology. There are both standardisation links and conversion links. Standardisation links evidence the company's standardisation policy and interlink one or more pieces of knowledge, often in an arbitrary or empirical manner. One then becomes dependent in relation to the other and vice versa. These links are strongly attached to the data of which the knowledge is made up. Thus, to reduce expenditure linked to diversity, a Renault-DIM designer working on a screwed assembly is obliged to choose the dimensions of a screw according to a standard configuration table. For example, this type of table only contains a choice of screw length limited to 15 or 23 mm if a 6 mm diameter screw has been selected. Conversion links evidence the evolution of knowledge according to its use context. They are not attached to the data but to the semantics of which the knowledge is composed. Let us take the example of the drilling of a screwed assembly support part. Knowledge of the piercing base diameter and the piercing base angle can be used as they stand in an upstream design activity when the depth of the drilling cone base has to be used for a downstream design activity. However, this knowledge is interlinked (independently of the data to which it is linked) by the conversion relation:

"Depth of the piercing base cone = diameter of the piercing base/2 × tan(piercing base angle)"

Thus, to retain consistency in the execution of upstream and downstream activities for the case in point, the dependency of the depth of the piercing base cone in relation to the diameter of the piercing base and piercing base angle must be taken into consideration. However, the "dependent", independent" and "unrestricted" statuses of a piece of knowledge fully depend on the order of specification of the knowledge and therefore on the design process. If we take the previous example in the context of a design loop, the upstream and downstream activities are reversed. The status of the piercing base cone depth dependency will switch to independent whereas the independence of the piercing base diameter and piercing base angle will switch to dependent.

As a result, the knowledge modelling we propose to study involves adding qualificative and semantics types of criteria, the links existing between pieces of knowledge. Our information system must also demonstrate flexibility when using these links to satisfy that of the design process.

2.3 Knowledge Sharing

A multitude of players are involved in the execution of a project who must all share their knowledge. The well-known professional sector-project organisation used by industrial companies [10] reveals the manner in which sharing should take place. Specific sector teams generate knowledge for their sector of activity. This knowledge must then be deployed in project teams. Several methods of deployment exist: secondment of people from sector teams to project teams, putting in place people responsible for contacts between professional sector teams and project teams or providing project teams with tools encapsulating professional knowledge: IT application documents, knowledge objects, etc. Our work will be oriented towards this last method.

First of all, knowledge must be easy to access. To meet this requirement, an increasing number of integrated information systems are being developed, in the field of CAD in particular [11, 12]. Users therefore remain in the same environment. However, we do not wish to restrict ourselves to this fully integrated context which is not widespread at Renault-DIM at the present time.

In addition, the knowledge must be presented in a manner tailored to the professional sector view of the person requiring it. Drieux [13] has developed the concept of the downstream numerical model along these lines. This concept designates "numerical models derived from those of the design department or other downstream models previously generated", adapted according to the "product views necessary for simulation activities." In this calculation-oriented work [13, 14] he principally looks at the shape adaptations to be implemented on the numerical model. In our study, we are looking at the adaptation of knowledge in more direct interaction with users. This is often evidenced by numerical or text types of data (see Sect. 2.1).

One way of satisfying these two issues would consist of retrieving knowledge and taking it directly to the professional application gateways, that is to say, the applications dedicated to the activity of an identified sector, used at operating level. Here we ensure that the knowledge is inserted as close as possible to the product specification, a view adapted to that of the user as it corresponds to the view of his professional application with easy access for the user. An approach of this kind assumes that our information system is able to interface with professional applications. This objective will be achieved by the use of a knowledge vector. It is also the choice made in the SOA concept (Service-Oriented Architecture) [15]. This vector should be based on the most standard unique format accepted as an interface with the company's professional applications.

3 Proposal

3.1 Solution Architecture

Integration of the requirements mentioned above has led us to propose the architecture for our solution in Fig. 2. It is based on the implementation of an information system that we will call the logistics system. The aim of this system is to manage the mapping and transfer of data between professional applications automatically and therefore acts as the design logistics reference. It does not meet artificial intelligence needs (complex inference mechanisms) as proposed with the Knowledge Intensive Engineering Framework [16] for example.

A professional application is presented here as an information system offering access to refined granularity knowledge. In certain cases, this knowledge is collected in files, the management of which is delegated to an information system or database (case of CAD files managed in PDM (Product Data Management)). Professional application A represents this situation. In other cases, the professional application and database can be encapsulated, thus forming the same information system (situation represented by professional application B).

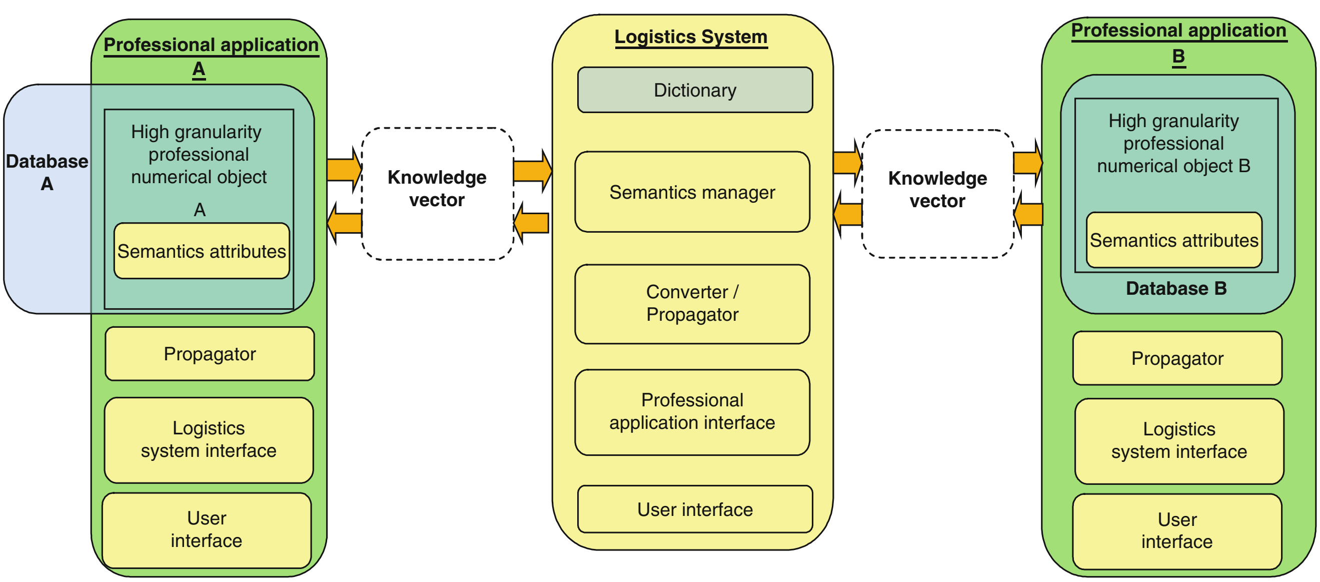

Fig. 2 Architecture of the proposed solution

The dialogue between professional applications and the logistics system is managed by a unique vector. The role of this vector is to support the transfer of knowledge. It must be chosen in such a way as to facilitate to the greatest possible extent interfacing with all professional applications aimed at the exchange of knowledge.

We will give details of the IT modules required for our architecture below.

3.2 The Dictionary

The role of the dictionary is to officially approve all the data to be shared. It consists of a knowledge base which provides the data with all the necessary semantics for comprehension and translation into a defined professional context. The foundations of the datamodel around which this dictionary is established are given in the UML diagram [17] in Fig. 3."

The data class represents the data to be shared (e.g.: " 6 ", "brass"). By instantiation of this class in the dictionary, it is possible to approve standard data (such as the values of all screw diameters authorised for use in design) or "undefined" data (data liable to change during design). The data definition class represents the semantics associated with data (e.g. "diameter" for datum "6" or "material" for datum "8.8 steel"). A datum is associated with only one data definition. A data definition is associated with at least one datum. The organisational context, functional context and structural context classes enable the following questions on data to be answered, respectively (e.g. "6") and its semantics (e.g. "diameter":

- Who does this data belong to? (example : "standard professional application"),
- What is this data used for? (example: "screwed assembly function"),
- What does this data belong to? (example: "screw")

The semantics of data may be linked to several organisation and functional contexts. For example, for the organisational context, the diameter of the air intake duct may be used both by the thermomechanical sector application and by the design department CAD modeller. However, these same semantics may only refer to one single structural context. In view of the granularity of the knowledge managed by our system, the structural context helps to reinforce the semantics of a datum by enlarging the possibilities of its "belong to" specification to a larger set. Vice versa, any one same context may be linked to one or more items of data.

As far as a knowledge network is concerned, it is modelled by creating a link between several data or several data definitions. These links are described in the datamodel by the notion of "flow" as they represent the notion of the course taken by the knowledge: one or more elements of knowledge establish others or enable others to be defined. They therefore flow in one direction (a reciprocal link being represented by two links running in opposite directions to one another). The interdata flow class represents the dependent links of the value of the data. They are normally standardisation links. As the links exist independently of data (for example, the formula linking the piercing base diameter and the piercing base angle) are data interdefinition flows. In the same way as for data, a flow is linked to only one definition reflecting its semantics. For example, a data interdefinition flow can represent a law of physics. A flow definition is linked to at least one flow (interdefinition or interdata). Moreover, the organisational and functional context of a flow must be specified if the data or data definition to which it refers might be linked to several organisational or functional contexts, respectively.

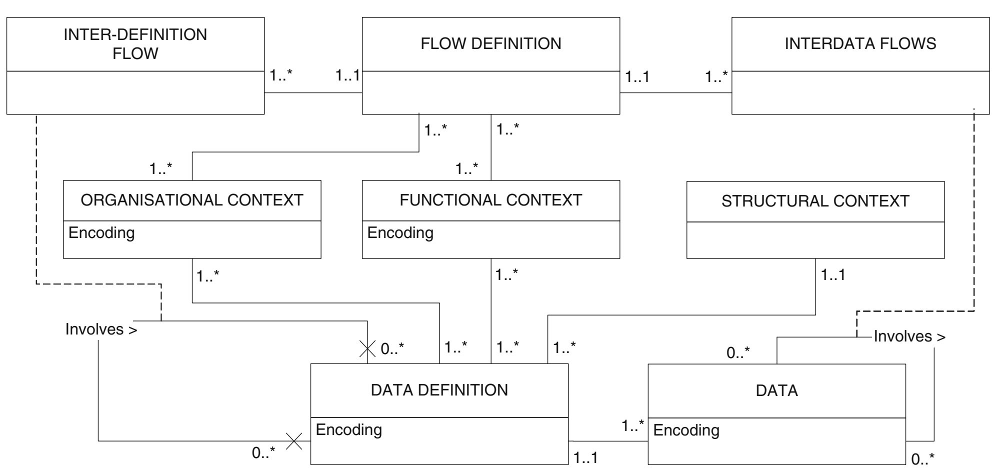

Fig. 3 Dictionary class diagram

The encoding attribute associated with several datamodel elements is intended to facilitate interoperability between the applications to participate in data exchanges, the encoding (sequence of digits and possible letters) being representative of the element in question).

It is notably apparent that flows are not encoded. In fact the purpose of the information system is to enable the exchange of knowledge. Its aim is not to exchange the interdefinition or interdata flows themselves. There are numerous reasons justifying this approach: the links between data are generally more representative of professional knowledge than the data itself and are therefore subject to a high confidentiality constraint (an observation notably made at Renault-DIM, it often represents core business). The advantage of exchanging links apparently resides in the fact that it is not necessary to go through a logistics system to test different data configurations. However, this represents a loss of indicators concerning the design process since these operations will be masked, which is something we wish to avoid. The logistics system therefore remains the sole owner of these flows.

3.3 The Semantics Manager and Semantics Attributes

The objective of the logistics system semantics manager is to ensure semantic consistency of data called upon to transit from one professional application to another. In order to execute its task, it relies on semantics attributes associated with each datum in a professional application. These semantics attributes encapsulate the data semantics via observance of encoding implemented in the logistics system dictionary. The content of semantics attributes is dependent on the activity carried out by the professional application. It is made up of encoding for "functional context", "data definition" and "data" elements of the classes diagram. The manager is then responsible for verification of the encoding contained in the semantics attributes with respect to those approved in the dictionary and also for the life-cycle of these attributes as regards "data" encoding (data being liable to evolve over the course of the design process).

3.4 Propagators and Converters

Propagators are present in both the logistics system and professional applications. They are information system modules that enable knowledge to be published or extracted to or from a knowledge vector. The publication of knowledge consists of writing the data and the associated semantics attribute in the vector. The extraction of knowledge consists of updating or verifying the knowledge contained in the professional application according to that contained in the vector. The user manages the completeness of transmitted knowledge. He is helped by indicators provided by the propagator module to know what knowledge has been verified and updated. In addition, a certain level of knowledge consistency will be guaranteed by exchange restrictions between inadequate professional numerical objects (see conclusion).

The converter is a specific logistics system module that handles the conversion of knowledge from one professional application to another, taking data interdefinition or interdata flows specified in the dictionary into account.

3.5 The Interfaces

Logistics system interfaces on the professional application side and professional applications on the logistics system side enable both tools to come into contact. This mainly involves jointly indicating the end of a knowledge publication or extraction. This signal enables automated sequencing of the activities of each system.

User interfaces handle interaction operations with a user for each tool. For professional applications, this is an extremely modest tool that enables the user to initialise an exchange. The user thus calls up the logistics system user interface from his professional application and via the logistics system interface.

The logistics system user interface is a more complex module. It enables the user to specify a set of information necessary to carry out an exchange:

- The client application and provider application. The status of the application from which the exchange is initialised is not fixed. As a result, the exchange may be made according to a "push" or "pull" logic.
- The functional context in which the exchange is made (the flows taken into account may differ according to the functional context chosen),
- A possible selection of the knowledge to be studied. In a "push" logic by default, all the knowledge processed by the provider application is transmitted and in a "pull" logic, all the knowledge processed by the client application is requested.

This interface calls for the setup of a query generator for the selection of knowledge involving standard data. The latter will help the user to select the knowledge network he wishes to study in a consistent manner.

4 Application

The application case we initialised covers the problem of the specification of a screwed assembly. In this context, it involves carrying out an exchange between the commercial CAD application and a tolerance stack-up application (internal Renault application) in a "push" logic. The scenario is therefore as follows:

1. The designer dimensions his screwed assembly.
2. He transfers automatically, via the logistic system, the knowledge defined (nominal dimensions) to the dimension chain application.
3. He makes the calculation of his chains of dimensions in the appropriate application thus rebalancing the nominal dimensions.
4. He transfers automatically, via the logistic system, the knowledge of the dimension chain application acquired to the CAD application.

The medium chosen for the data dictionary is the Excel file shown in Fig. 4. The professional applications concerned are a CAD application and a dimension chain calculation application. The CAD model is shown in Fig. 5. Anapplication extract is shown in Fig. 6. The format of the knowledge vector chosen is Excel.

VBE (Visual Basic Editor) was used for implementation of the CAD application information system modules and VBA (Visual Basic for Application) for those of the dimension chain calculation software. The logistics system was implemented using VBA. The semantics attribute associated with each piece of knowledge is specified by using the "comment" attribute associated with each parameter for the CAD application (Fig. 5) and with each Excel cell for the dimension chain application (Fig. 6). The "data" and "data definition" classes of the dictionary datamodel were specialised in order to integrate the knowledge typology indicated in Sect. 2.1. The user interface query generator of the logistics system was not implemented for the purposes of this initial validation stage of our architecture. In fact, the default logic was applied: all the knowledge processed by the provider application was transmitted and the client application can only extract from the vector the knowledge for which it possesses the semantics attributes.

The various steps of an exchange are listed in the table in Fig. 7.

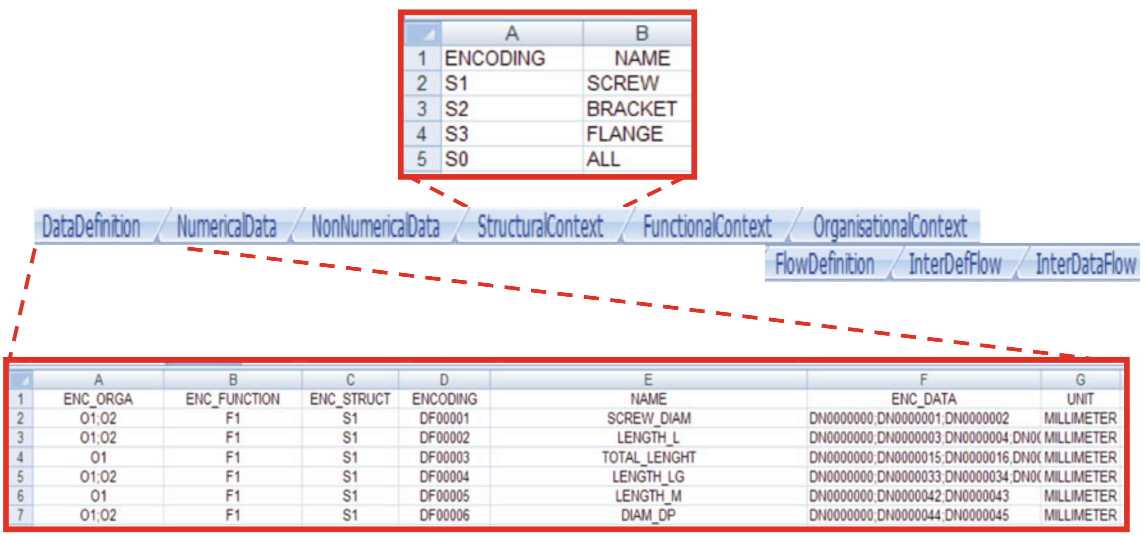

Fig. 4 Implementation of the dictionary

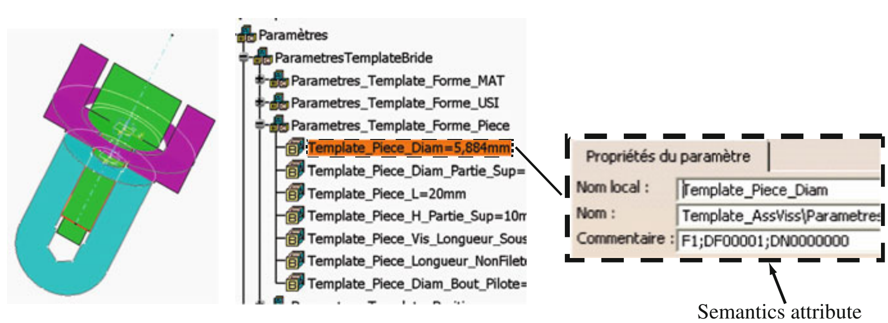

Fig. 5 CAD model

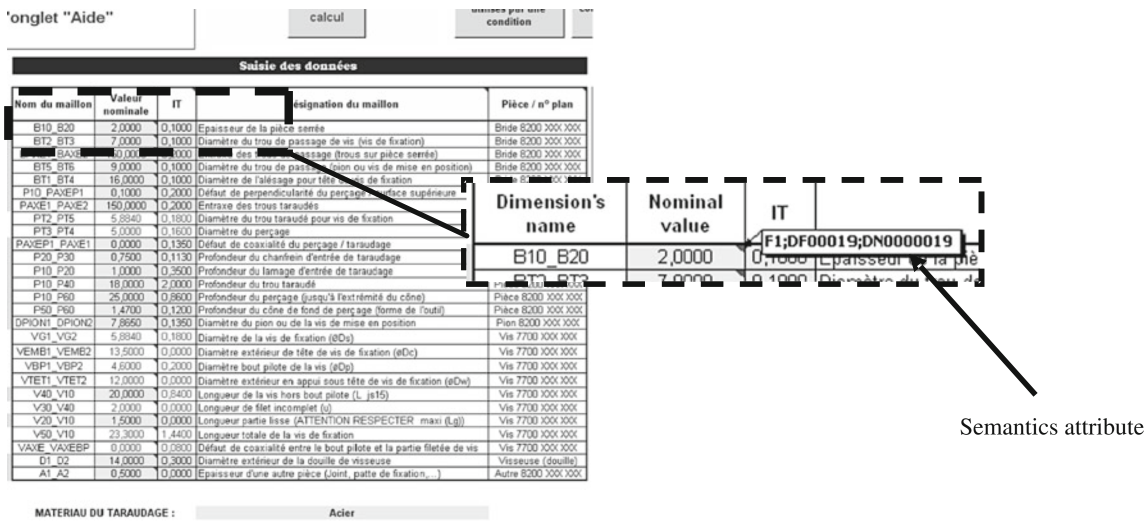

Fig. 6 Extract from the dimensions chain application

Steps	Description	Key information system used
1	Specification of the client organizational context (representative of the client application), the provider organisational context (representative of the provider application) and the functional work context by the user.	-The « user interface » of the professional application to launch the exchange, -The « user interface » of the logistics system to specify expected information.
2	For each piece of knowledge : Publication by the provider professional application of the semantics attribute and associated data in the provider vector.	-The « professional application interface » of the logistics system to launch the « propagator » of the provider professional application -The « propagator » of the client professional application to publish the semantics attributes in the provider vector.
3	For each piece of knowledge : Processing of the knowledge published by the logistics system. Case 1: the semantics attribute makes reference, within the dictionary, to knowledge that has been approved by both the provider and client application organisational contexts. In this case, the semantics attribute and associated data are published in the client vector. Case 2: the semantics attribute makes reference, within the dictionary, to knowledge approved only for the provider application organisational context. In this case, an algorithm enables the user to determine whether this knowledge occurs in the appropriate inter-definition flows of the dictionary. Every flow must occur at knowledge input for the provider application and knowledge output for the client application. Moreover, its functional context must correspond to the one defined when the exchange is initialised. If one of these conditions is not met, the flow is not studied. Otherwise, the flow is studied and the new knowledge defined. Their semantics attribute and associated data is then published in the client vector..	-The « semantics manager » of the logistics system to make sure semantics attributes makes reference to a piece of knowledge specified in the dictionary, -The « converter » of the logistics system to adapt knowledge from the provider professional application toward the client professional application if necessary, -The « propagator » of the logistics system to publish the semantics attributes in the client vector.
4	For each piece of knowledge : Updating of the client professional application data by matching the semantics attributes of the client vector and those of the client application.	-The « professional application interface » of the logistics system to launch the « propagator » of the client professional application, -le « propagator » of the client professional application de l'application métier client to update its data.

Fig. 7 The various steps of an exchange of knowledge between professional applications

5 Conclusion and Prospects

The application case developed has enabled us to validate the fact that the logistics system architecture enables the automated exchange of knowledge to be supported between two professional applications in the following conditions:

- Professional applications satisfy the architecture proposed (generic information system modules and semantics attributes).
- The knowledge studied is modelled according to the dictionary class diagram.
- The knowledge studied does not consist of standard data.
- The links between pieces of knowledge (interdefinition flows) are modelled in the dictionary with the necessary formulae.

In terms of prospects, modelling of the interdata flow concept should be studied via a second application case. This application case should enable us to validate the possibility of the automated exchange of data between a knowledge management system containing standard data configurations and a professional application enabling knowledge to be defined in the course of a project. This work, on overall validation of the class diagram proposed for the dictionary, will have to take into account previous studies on knowledge ontologies [18, 19] and semantic web [4] for future implementation.

In addition, we will need to propose a means of integrated orchestration of knowledge exchanges made possible by our system. It will then involve defining who can share what, at what time, managing exceptions and collecting indicators of implementation of the design process on an operating level. The purpose of the latter will be not here to capture design rationale [20] but to help project management. The most suitable tools at present to deal with this problem are workflows [1, 21]. Process modelling resources have already been tackled [22, 23] by taking flexibility needs into account [24, 25]. Indicators tailored to the design process have also been proposed [26].

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Knowledge Based Engineering Approach Through CAD Systems: Results of a 2 Years Experimentation in an Industrial Design Office

J.B. Bluntzer, J.C. Sagot, and M. Mahdjoub

Abstract In the context of the automotive industry, OEM and suppliers are setting new processes in order to reduce the product costs and decrease development time. These new approaches affect the design process, which become today more collaborative in the globalization of the market. From several years, many new approaches using simultaneously new tools were implemented in industrial companies. The main purpose of this chapter is to introduce a new design process including the new CAD tools, which was implemented in a design office since a couple of years, and present the result of 1 year use.

Keywords Routine engineering · Product lifecycle management · CAD modelling · Knowledge-based engineering

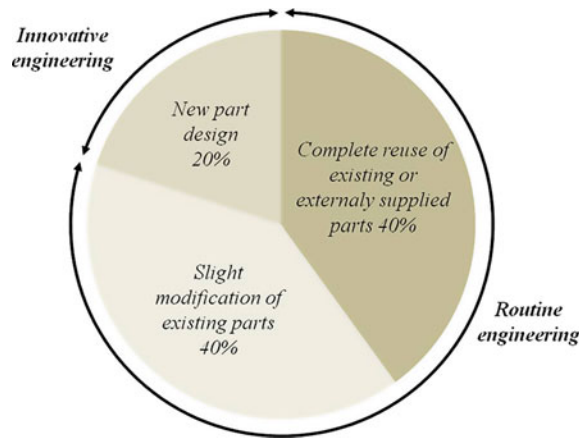

Fig. 1 Product dichotomy in routine and innovative engineering tasks inspired from Rezayat

1 Introduction

This chapter presents an industrial implementation of a collaborative process of routine engineering integrating, in the early stage of the product lifecycle, expert knowledge in order to increase productivity in design of mechanical products. Indeed, if we consider all the parts contained in a complex product, for instance the case of an automotive product, Rezayat [1] defines that 40% of the components are a complete reuse of existing or externally supplied parts. In addition, 40% of the components are slight modification of existing parts. Therefore, only 20% of the parts are newly designed.

The Fig. 1 describes this product dichotomy in order to split the product in to parts, the innovative engineering (20%) and the routine engineering (80%) [2]. In this context, the main objective of this chapter is to experiment a new methodology in order to decrease time devoted to such a routine engineering, the aim being 50% of the time against 80% today. This tends to allocate more resources for innovation, namely 50% of the time against 20% today.

In this chapter, we present firstly our research objectives in terms of accelerating the routine engineering through a knowledge management approach [3]. After the presentation of the research hypothesis, we describe a part of our global design approach, which was experimented in an industrial design office. After the presentation of the tools and technologies used in this experimentation, we expose the result of 1-year experimentation. These results allow to conclude of the proposed methodology and to elaborate some scientific and industrial perspectives.

2 State of the Art and Scientific Objectives

The activities performed daily by an engineer in a center of research and development, for example in the automotive industry can be described as multitask and parallel activities [4]. First, the designer extracts the functional parameters

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from the initial requirements. This requirements can be provided by the final consumer in the case of an Original Equipment Manufacturer (OEM), or directly from him in the case of a supplier. After this extraction, the designer proposes some technical solutions answering the requirements. In this step, many design or innovative methods (brainstorming, TRIZ, etc.) are able to help him. But in parallel, he need to use his own technical experiment and his own knowledge. In order to build the proposed solution, he use the standard components available through standard catalogs or into the standard database of the company. Once all this information put together, it is able to perform the CAD model of designed product.

Today, this traditional approach of the design process can be improved with the capitalization of the previous cases of the industrial company. Through experience feedbacks, it is possible to extract the data, information and knowledge from these previous cases. This improvement can be also done into the CAD system with the capitalization of CAD models including parameters and engineering rules in order to be reuse in new digital mockup.

Resulting from this observation, our main research objective is to search new design methods and new tools in order to improve the design step of the CAD model. This approach aims to reduce the time dedicated to routine engineering in order to devote more time to innovation.

In order to implement our new design process, the following hypotheses are defined:

1. The CAD model integrates other aspects than the geometrical information, like the structural, functional, dynamical or physical information [5].
2. The CAD model is shared into three domains: project, product and process [6].
3. The CAD model integrates all information coming from the experiences of the company like the engineering rules.

Since 1996, our research team has deployed several methods and tools working in the area of the technical data management [7] coupled with the knowledge information. Founded of the systemic paradigm, our approach considers all aspects and steps of the design process. Using this approach, we are able to work in initial design, qualified as innovative engineering, and in redesign, qualified as routine engineering.

In this context, we can expose our scientific problematic into three points:

1. How to confirm that the design process is based on the engineering rules of the company which was extract in the previous cases?
2. How to reuse previous CAD models including engineering rules into the new digital mock-ups?
3. How to interconnect the different actors of the company in order to distribute the data and information extracted in the previous cases?

An extract of our global design methodology answering these three points is described in the next section.

3 Methodology and Tool

Today, the design process become more and more collaborative [8]. In the global context of the economy, this collaboration become international and multicultural. In this context, the design methodologies evolves in order to integrate this new constraints. For example, the scientific research and the development of new industrial tools in the area of the Product Lifecycle Management (PLM) [7] confirm this new industrial need. In parallel, products are more and more complex, integrating more than one expert skill. For example, for an automotive key, the design of this product needs to integrate skills in the following area: plastic design, electronic design, sheet metal design and styling.

In order to design the product, each actor uses one type of tool. The next section describes one of the main tool used in a design process.

3.1 Design Tool

Through the design process, several actors use many tools in the whole product lifecycle. For instance, the project leader of an industrial company uses several tools like an ERP (Enterprise Resources Planning), a PDM (Product Data Management) and offices tools. Moreover, it we consider the mechanical designer involving in the same area, this actor use daily Computer Aided Design (CAD) tools. This kind of tool, which is today called parametric, allows to the designer to integrate some design parameters, which will drive the geometry of the CAD model. This parameters can be geometrical (distance, diameter, angle, etc.) but can also be functional (Stress, force, colour, etc.). This type of parameters comes directly from the initial requirements transferred from the project leader of the industrial company. In parallel, with the development of the knowledge management, the industrial company allows resources in order to formalize his knowledge. One of this formalization can be the redaction of the engineering rules. In this case, with an implementation of these engineering rules into the CAD model, the designer is now able to link the functional parameters to the geometry through the engineering rules, which drive directly the geometry of the CAD model. The Fig. 2 showa simplified model

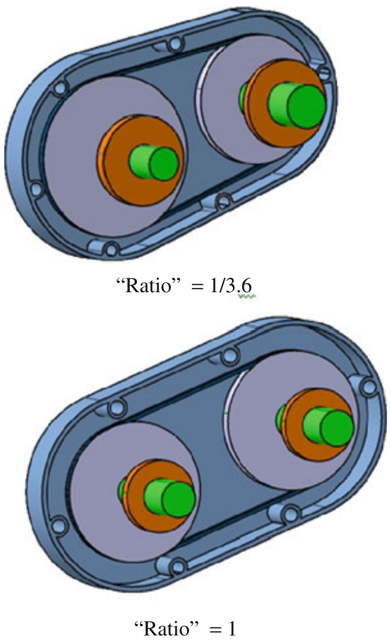


Fig. 2 Example of a mechanical reducer driven by the functional parameters "ratio"

of a mechanical reducer driven by the functional parameters called "Ratio".

In this example, if we switch the functional parameter "Ratio" from 1/3,6 to 1, the digital mock-up is instantly adapted. In fact, the diameters of the rotating parts are linked to the "Ratio" parameter through engineering rules and are modified when the switch is operated. This simple example, which as been previously published [9], shows how the parametric CAD tools work.

In our experimentation, one industrial CAD tool has to be chosen in order to follow the implementation of our new design approach. If we consider the automotive industry, the choice performed on the main used tool in this kind of industry is CATIA v5 from Dassault System. To confirm this choice, we can consider the Detroit automotive salon beginning 2009. In fact, 90% of the exposed vehicle was designed with this tool [10]. Moreover, this tool allows the designer to create this new kind of model using a specific technology called "Knowledgeware", in order to built a knowledge based engineering approach [11].

This technology allows also to the designer to create some generic parts called templates. These specific parts, which include functional and geometrical parameters linked by engineering rules, can be used generically from one assembly to another.

In the reducer example, the bearing can be consider as a template. The diameters and the thicknesses of this part will be driven by the diameters of the assembly axis.

Moreover, we can consider two type of templates based of the use of the designer. First, the type of "template" called "specific" allows the designer to create specific feature on the final product. Second, the type of "template" called "control" allows the designer to control the final product in its environment. The two type are described on the two following figures.

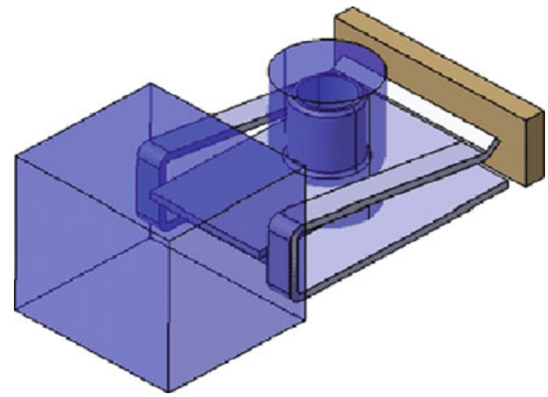


Fig. 3 Example of a part "template" from the type "specific"

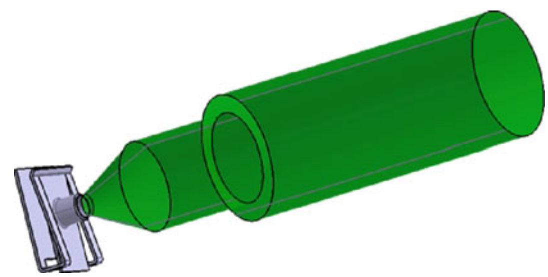


Fig. 4 Example of a part "template" from the type "control"

On the Fig. 3, we can show a nut sheet metal (in grey) and two feature. This "specific template" creates and suppresses geometries using a CSG (Constructive Solid Geometry) approach. In this example, when the designer implements into the CAD model the nut sheet metal, he imports simultaneously the stopper (whole area) and the undercut (transparent area). Using the Boolean operator, he is able to add the stopper and remove the undercut in order to implement the technical solution involving around the nut sheet metal.

On the Fig. 4, we can show a nut sheet metal (in grey) and one feature (transparent). This "control template" allows the designer to control if the screw gun used in the assembly process will not impact the environment of the product. As "control template", we can consider each template that will help the designer in his check process, like for examples the controls of the product bounding box, the weight of the product or the number of product that can be stored in a container.

The design methodology proposed in the following section is based on these parts called "templates" which allow improving the routine engineering.

3.2 Design Methodology

Using the definition and the typology of the templates defined previously, we are now able to propose a methodology that can be implemented in a design office. The methodology studied in this chapter is an extract of our global approach in new product development.

The extract of our global methodology model, proposed on the Fig. 5, is divided into tree different steps performed by tree different actors which evolve in a design office of an automotive industry.

The project manager involves in the first step. This actor needs to define at the beginning of the design process the requirements that the product needs to answer. In this proposed methodology, this actor communicates the requirements directly to the designer. Many tools are available to perform this step, for instance we can cite the functional analysis approach [12, 13]. But this step is not detailed in this article.

In parallel of the first step, the second step is performed by the CAD expert. This actor is in charge in the design office to build the control and specific templates. In this approach, we considers that the CAD expert build the templates after the identification of special requirements from the designers. Moreover, the CAD expert needs to integrate engineering rules into the CAD model. In the global methodology, which is not presented in this chapter, he use the Knova-Sigma methodology [14] in order to extract it. After that, when the generic model is built, the CAD expert store it in a Generic CAD models database. This database is accessible by each designer of the design office. In this step, we introduce a new actor called "CAD Expert". Effectively, the creation of templates needs some skins in IT development (for example Visual Basic from Microsoft) mixed with mechanical skins.

The third step, performed by the designer, is a standard step of the design process. The designer, through the initial requirements, build le product. The main difference is that he his able to use template in order to perform his work. Through this step, the designer choose on the database, the template he need to build the final product.

The next section exposes the experimental plan built in order to know if and how the proposed design process is used.

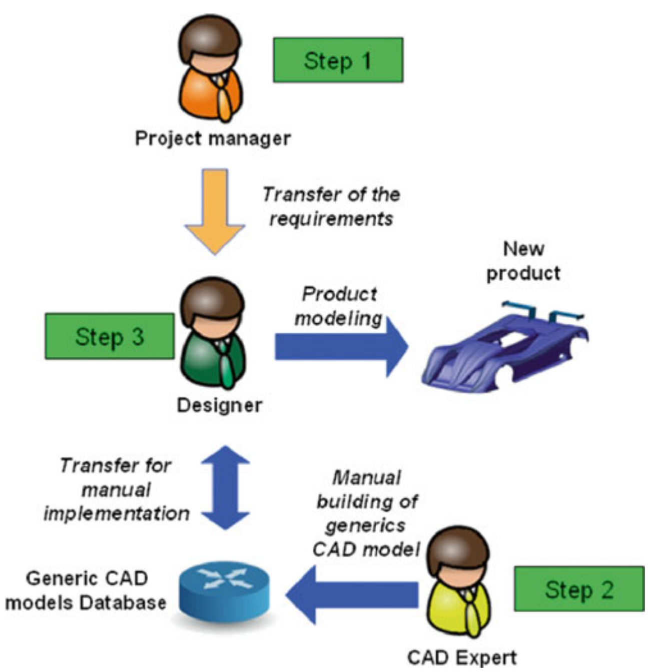


Fig. 5 Methodology model

4 Experimental Plan

The main objective of this chapter is to propose the result of the implementation of this method in a design office in the automotive industry. In order to expose this result, we need to set up an indicator of the usage of this methodology. The next section proposes a follow-up approach in order to obtain the needed information.

4.1 A Follow-Up Approach

The proposed methodology is founded of the hypothesis that the designer, in the second step, will use the generic models built by CAD expert in the first step.

In order to follow-up this kind of use, we propose to track the implementation of the templates in each new product, which is designed in the design office. At each implementation operated by the designer actor, we need to check the three following point:

1. The implementation date: allow to know when the template is implemented in a new project
2. The type of "template": allow to know if the "template" is "specific" or "control"
3. The name of the impacted project: allow to know on which project the "generic" is used

In resume, these three data coupled will allow to know which kind of generic type is used and at witch moment of the project the implementation was done. In this context, this information will confirm if this approach is accepted by the designer actor of the industrial company.

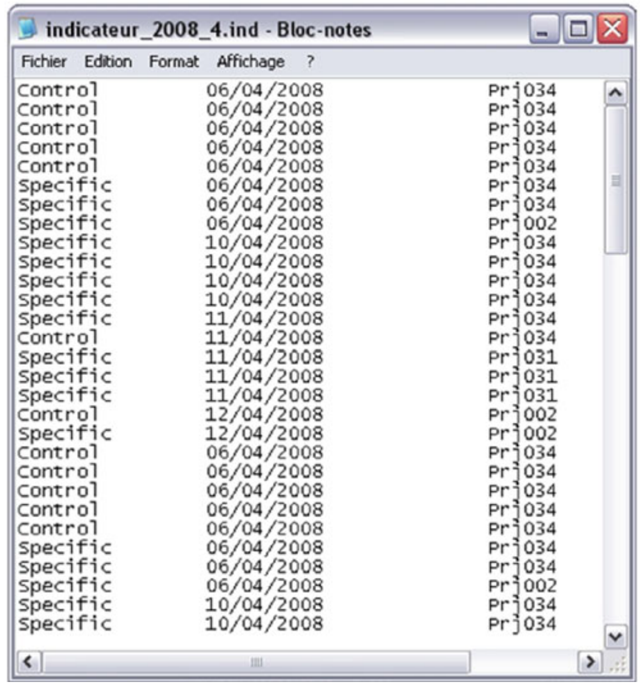
4.2 Technological Choice

In order to track the "template" usage, a technological choice based of the CAD systems is developed. CATIA v5 working on Microsoft Windows station includes the technology called Visual Basic Application. This technology allows to customize the CAD application in order to add some specific plugging. This kind of plugging is used in order to add specific features into the original CAD system.

Combined with the "templates" model, this technology allows to initiate the algorithm, exposed on the Fig. 6, at each instantiation.

The text file used in this algorithm is stored on a shared database server between each designer of the industrial company. In order to lighten the text file, an other algorithm is implemented. This new algorithm creates each month a new tracking text file.

The next section exposes the result of this tracking for a 1 year use.



Control	06/04/2008	Prj034
Control	06/04/2008	Prj034
Control	06/04/2008	Prj034
Control	06/04/2008	Prj034
Control	06/04/2008	Prj034
Specific	06/04/2008	Prj034
Specific	06/04/2008	Prj034
Specific	06/04/2008	Prj002
Specific	10/04/2008	Prj034
Specific	10/04/2008	Prj034
Specific	10/04/2008	Prj034
Specific	10/04/2008	Prj034
Specific	11/04/2008	Prj034
Control	11/04/2008	Prj034
Specific	11/04/2008	Prj031
Specific	11/04/2008	Prj031
Specific	11/04/2008	Prj031
Control	12/04/2008	Prj002
Specific	12/04/2008	Prj002
Control	06/04/2008	Prj034
Control	06/04/2008	Prj034
Control	06/04/2008	Prj034
Control	06/04/2008	Prj034
Control	06/04/2008	Prj034
Specific	06/04/2008	Prj034
Specific	06/04/2008	Prj034
Specific	06/04/2008	Prj002
Specific	10/04/2008	Prj034
Specific	10/04/2008	Prj034

Fig. 7 Example of a text file containing the following tracking data: the type, the date and the project

5 Result of the Follow-Up

This sections, divided in two parts, presents the capitalized data in the industrial company and the result of the tool. Effectively, CATIA v5 linked with the PDM allows to know from which project the working CAD model was checked-out from the PDM.

The name of the tracking file is composed of month and the year in order to stored into a specific data base.

To read this file, which is a text file with the extension ".ind" for "indicator", we need to open it into a spreadsheet software. The software used in our case is Microsoft Excel. In this software, this file is processed in order to obtain some specific results.

These results are exposed in the next section.

5.1 Capitalized Data

As exposed previously in this chapter, the design methodology implemented since 2 years in a design office of the automotive industry allows as generated 24 tracking files (one per month). The Fig. 7 shows the structure of the text file.

We can see three different columns on the Fig. 7.

The first column on the left capitalize the template type. The previously defined type are exposed ("Control" and "Specific"). The second column in the middle capitalize the date of the "template" instantiation. This date use the following format: dd/mm/yyyy. The third and last column on the right capitalize on which project the "template" was instantiated. In order to obtain this information, we use the link performed between the PDM tool and the CAD

If "template_X" is used

Write in text file the "template type", the "date" and the "project name"

End if

Fig. 6 Tracking algorithm implemented in each "template" of the industrial company

5.2 Result of the Tracking

Resulting of the actual context of the economy, we choose to present only the result for the first half period of the experimentation. The result after September 2008 are not pertinent and expose not the reality of the daily work done by a design office in the automotive industry.

The twelve tracking files was introduced into the spreadsheet software in order to process the data which was capitalized during the identified period.

In order to expose the result, the Fig. 8 illustrate the use of the two type of tracked templates, the specific and the control. This figure shows the percentage of the use of one type of template in comparison with the other for each studied month.

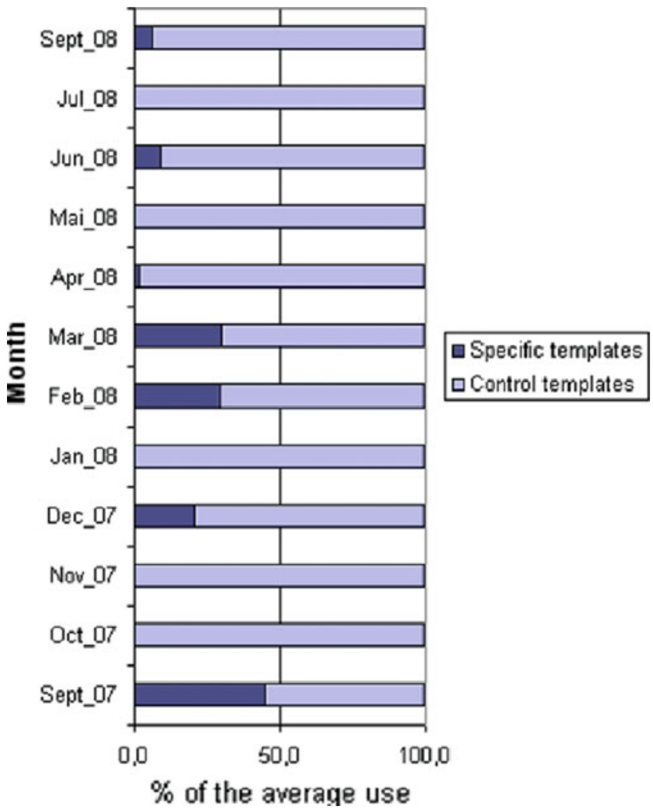


Fig. 8 Result of 1-year use of the described design process

We can observe on the Fig. 8 the graph with the average use in abscissa and the month in ordinate. It turns out that two use patterns emerge, a use described as "continuous" and another that we can call "periodic". The generic models of "control" have a continuous utilization rate and the generic models "specific" have a periodic utilization rate.

From this study, we can define two different observations:

1. The use of "control generic" is high and continuous over the time.
2. The use of "specific generic" is low and punctual over the time.

Following these observations, we must understand why designers do not use the same way the two types of generic models. This reflection is discussed in the following paragraph.

5.3 Result Discussion

We can write that the methodology proposed in this experimentation works technically. Indeed, the methodology allows to be more reactive in routine design using generic models drive by some functional and geometrical parameters.

However, according to statistics of industrial use, this methodology is not or rarely used by the designers of an industrial company evolving in the automotive area. Indeed, its foundation is based mainly on the use of "specific templates". However, we determined that the use of such generic models is low and punctual over the time. Therefore, we must establish the causes of this non or rarely use.

Through a personal interview with each of the designers in the design office, it shows two distinct trends.

The first issue identified is a lack of information and lack of specific training. Indeed, initially, the designers say they do not know the existence of specific generic models. Thus, they can not use them.

Secondly, they state that although they are aware of some "specific generics", they can not use them and, thus, they do not use them and would not spend too much time to understand its instantiation.

The second question is the rapid turnover of the integrated engineering rules associated particularly in the areas of complex design. The designers of the design office use the "specific template" only at the beginning, but can not use them after. In fact, the engineering rules contained into the specific model is quickly obsolete. Indeed, the return on investment in the capitalization of knowledge in the form of generic models is difficult to justify to the designers of the design office and thus is not applied.

The next section allows us to discuss these experimental results to identify possible new methodological guidelines.

6 Conclusion

Through this chapter, we established a design methodology that allows the designer of a design office to improve the time dedicated to the routine activities. In order to do this improvement, the hypothesis of the use of "generic" CAD model into the design process is established.

In order to validate this hypothesis, an implementation of the proposed methodology is implemented in a design office of the automotive industry. To validate it, an experimental plan was set up. Using a tracking file, we are able to know if the proposed "templates" are used by the designers of the design office.

Though the tracking files obtained during the tracked period, we establish to type of "generic". The "control generic" which use the designer to control his design and the "specific generic" which use the designer in the implementation of technical solution into the designed product.

The result of this tracking exposes two reports. The use of "control generic" is high and continuous over the time

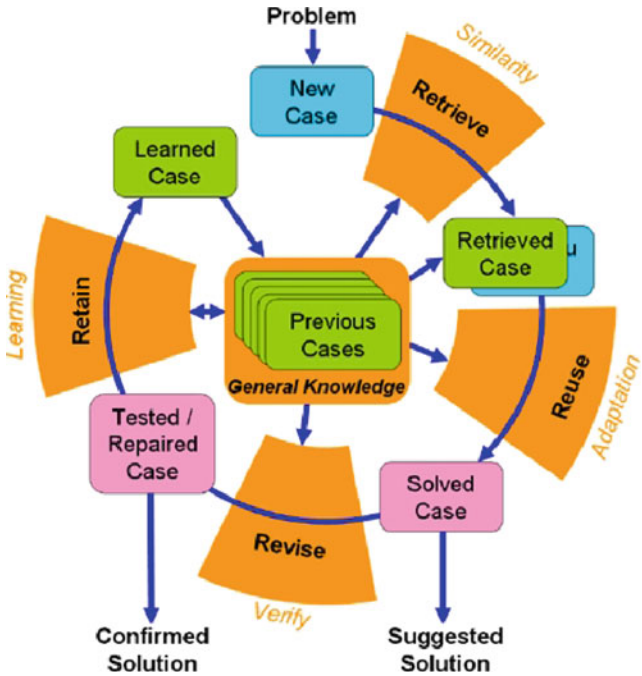


Fig. 9 Case-based reasoning model [9]

and the use of “specific generic” is low and punctual over the time. Why this main difference? After specific interviews with the different actor, we establish that the templates solutions built by the CAD expert are quickly obsolete. In order to up to date this template so quickly that the evolution of the integrated engineering rules, new hymen resources should be dedicated to this activities.

In this context, it is necessary to research other way to help the designer in these routine activities. Integrating a new paradigm should be necessary. The case based reasoning paradigm [15], describes in the Fig. 9, seems to be more adapted in the case of mechanical design.

In order to adapt this new paradigm in our design methodology, our future research work will consider how to define a type of knowledge founded of previous cases in order to be given to the designers in new projects.

After that, we need to define how to retrieve the previous cases stored into the data base. When the case is retrieved, we need to define how to reuse it in order to solved the case. The revision of the case will allows us to up-to-date the defined knowledge in order to be reuse in the next project.

Acknowledgment We sincere thanks our industrial partner which as been implemented this design method in his design office and allow us to expose this result.

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Patents as Resources for Creative and Inventive Design for Global Product Development

Computer-Aided Comparison of Thesauri Extracted from Complementary Patent Classes as a Means to Identify Relevant Field Parameters

G. Cascini and M. Zini

Abstract Patents are gaining a growing importance as a complementary source of technical information, since the information they disclose is not accessible in scientific and technical literature. Text mining technologies are emerging as a possible solution to increase the efficiency of patent analysis activities; besides, most of the existing systems are derived from general purpose applications that marginally leverage patents peculiarities. The authors are developing algorithm and tools fully dedicated to patent mining, i.e. information extraction from patent literature. The present paper aims at the identification of relevant technical parameters for a certain domain, through the comparison of thesauri automatically extracted from the given field of application and from its complementary patent classes.

Keywords Patent mining · Field thesaurus · Patent classification · OTSM-TRIZ · Network of parameters · Network of evolutionary trends

1 Introduction

The definition of competitive R&D strategies requires monitoring the evolution of technical systems in order to assess the maturity level of current solutions and to check the emergence of new technologies. Nevertheless, despite more than fifty methodologies with different characteristics and specific purposes have been proposed so far in this field [1], no universal methods are known. Besides, complementary instruments must be integrated according to the specific goal and data availability. Moreover, due to the huge amount of scientific and technical documentation nowadays produced in any field of application, these analyses are extremely time consuming.

Among the recent research developments which deserve a proper attention to improve the efficiency of innovation related activities, TRIZ (the Theory of Inventive Problem Solving) is gaining popularity as a means to systematize the analysis of a technical system and to identify opportunities of evolution.

A promising direction of research in this area is the definition of structured models representing in a concise format the challenges of a certain field of application in the form of networks of contradictions as proposed in [2], or in the form of network of evolutionary trends, as described in [3].

In both cases the domain knowledge is represented in terms of parameters and relationships between these parameters; the identification of the relevant parameters and the related links is a critical task which requires questionnaires to subject meta-experts aimed at making their knowledge explicit.

A complementary and extremely valuable source of information to support these analyses is constituted by patent databases: in facts, several studies have demonstrated that 80% of information contained in patents, is not available in any other source [4]. A further advantage of patents is related to their semi-structured format which allows adopting customized text-mining techniques to improve information extraction efficiency.

The authors are developing a set of complementary algorithms for patent mining. The goal of the present article is to show the preliminary results of a research aimed at building a model of domain knowledge in the form of a network of parameters. More in details, the paper details the process of construction of a domain thesaurus through automatic patent analysis and the criteria to compare thesauri extracted from complementary patent classes as a means to identify relevant field parameters.

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2 Related Art

Before than detailing the methodological approach and the computer-based system proposed in the present paper, it is worth to recall some fundamentals about the International Patent Classification. This section will summarize also some relevant outcomes of previous research activities carried out by the authors in the field of patent text-mining. Finally, previous works related to automatic thesaurus construction will be critically surveyed, to highlight opportunities and limits for their application in the patent field.

2.1 International Patent Classification

The International Patent Classification (IPC) system is a language independent hierarchical classification of patents and utility models according to the different areas of technology to which they pertain.

Inventions from any field are classified into 9 sections and further subdivided into classes, subclasses, main groups and subgroups (5th and lower levels).

The primary purpose of IPC is supporting patent documents retrieval, in order to establish the novelty and evaluate the inventive step or non-obviousness of technical disclosures in patent applications. The Classification, furthermore, has the important purposes of serving as [5]:

i. an instrument for the orderly arrangement of patent documents in order to facilitate access to the technological and legal information contained therein;
ii. a basis for selective dissemination of information to all users of patent information;
iii. a basis for investigating the state of the art in given fields of technology;
iv. a basis for the preparation of industrial property statistics which in turn permit the assessment of technological development in various areas.

According to the third objective of IPC, it is assumed that the patents belonging to a specific class constitute a meaningful sample of documents from where to extract the terminology of a certain field of application and the main technical parameters of such technological area.

2.2 The PAT-Analyzer Project

The authors are working on the development of new techniques and algorithms for patent analysis and comparison [6–8]. As a result of these previous experiences a prototype software system (named PatAnalyzer) has been developed with the following functionalities:

- identify the components of the invention;
- classify the identified components in terms of detail/abstraction level and their compositional relationships in terms of supersystem/subsystem links;
- identify positional and functional interactions between the components both internal and external to the system;
- identify the most relevant components of each patent for a given project according to a ranking criterion which combines the detail level of the description with components' occurrences in patent claims and with the Inverse Document Frequency, i.e. the "rarity" of each synset of the Thesaurus.

2.3 Automatic Thesaurus Construction

The word thesaurus derives from Greek and Latin and means "treasury or storehouse; hence, a repository, especially of knowledge; often applied to a comprehensive work, like a dictionary or encyclopedia". Numerous definitions of thesauri exist across fields such as computer science, artificial intelligence and library and information science [9–11]. They vary from quite modest definitions that do not specify types of conceptual relations, to more specific definitions that clearly define the conceptual relations. In [12] there is an example of a modest definition: "we define a thesaurus as simply a mapping from words to other closely related words". In contrast, Miller gives a more elaborate definition of a thesaurus as "a lexical-semantic model of a conceptual reality or its constituent, which is expressed in the form of a system of terms and their relations, offers access via multiple aspects and is used as a processing and searching tool of an information retrieval unit" [13]. The ISO 2788:1986 (Guidelines for the establishment and development of monolingual thesauri) standardizes Thesauri defining it as a "vocabulary of a controlled indexing language, formally organized so that a priori relationships between concepts (for example as 'broader' and 'narrower' are made explicit"). For the purpose of this work, it is adopted the broader definition: a thesaurus is defined as a structured system of concepts identified by collections of terms and hierarchical relationships between these concepts.

Manual thesaurus construction is a huge, time-consuming task of term selection, conceptual analysis and relational structuring of concepts and terms [10]; moreover, it is subjected to problems of bias, inconsistency and limited coverage.

In addition, thesaurus compilers cannot keep up with constantly evolving language use and cannot afford to build new thesauri for the many sub-domains that NLP techniques are being applied to.

There is a clear need for methods to extract thesauri automatically or tools that assist in the manual creation and updating of these semantic resources.

Methods for automatic thesaurus extraction can be roughly divided in two categories: Statistical methods; Linguistic patterns methods.

Statistical methods rely on the observation that semantically related terms will appear in similar contexts. These systems differ primarily in their definition of context (e.g. window of text, sentence, paragraph, grammatical context, entire document) and the way they calculate similarity from the contexts each term appears [14]. The simplest contexts to extract are the words surrounding term up to some fixed distance. Some approaches take the whole document as the context and consider term co-occurrence at the document level.

In [15] grammatical relations are extracted such as:

- term is subject of a verb;
- term is the (direct/indirect) object of the verb;
- term is modified by noun or adjective;
- term is modified by a prepositional phrase.

The relations for each term are then collected and counted producing a context vector for each term. Once these contexts have been defined, these systems define measures of similarity between context vectors and then use clustering or nearest neighbor methods to find related terms.

Linguistic pattern methods are based on the observation that patterns of co-occurring terms carry information about their semantic relations. These systems extract related terms directly by recognizing linguistic patterns which connect synonyms and hyponyms [16, 17]. In the pioneering work of Hearst [16], the use of linguistic patterns was suggested to discover hyponymy relations from unstructured text.

Patterns like

$$\text{such NP as } \{\text{NP}, \} * \{(\text{or} | \text{ and})\}\text{NP}$$

as in: "Works by such authors as Herrick, Goldsmith, and Shakespeare", or like

$$\text{NP } \{, \text{ NP}\} * \{, \} \text{ or other NP}$$

as in: "Bruises, wounds, broken bones or other injuries" can be used to extract hyponymy relations. From the examples it is possible to infer that "Herrick", "Goldsmith" and "Shakespeare" are all hyponyms of the term "author" and "bruise", "wounds" and "broken bone" are "injuries".

Previously described methods have a general purpose approach, relying only on mere text, without any other information available on the ontological structure of the concepts to be extracted and organized.

In the work by Shinzato [18] itemizations in HTML documents taken from the Web are exploited to identify hyponym candidate sets, statistical measures and heuristics are then used to select actual hyponyms.

The last described work suggests that, where available, the information conveyed by the peculiar structure of the analyzed document can be exploited.

The approach proposed in this work leverages patent structure and pattern of text to provide a semi-automated thesaurus generation system.

Focusing on invention components denominations as the thesaurus terms here identified, it is possible to exploit the semantic information conveyed with alternative denomination sets as defined in Sect. 3.1 to discover synonymy and hyponymy relations. The proposed approach is described in the following section.

3 Thesaurus Construction and Comparison

The present chapter is subdivided in two subsections, the first focused on the original algorithm developed by the authors for computer-aided thesaurus construction, the second details the proposed procedure to compare thesauri extracted from complementary patent classes with the aim of identifying the main technical parameters of their related fields.

More in details, with the aim of building a model of domain knowledge according to any of the approaches described in [2] and in [3], it is necessary to identify two different kinds of parameters:

- Evaluation Parameters, i.e. parameters to measure the level of satisfaction of system requirements;
- Control Parameters, i.e. any kind of design variable, property or feature controllable by the designer, which might impact on at least one Evaluation Parameter.

Control Parameters and Evaluation Parameters related to a specific technical field will be referred as domain parameters hereafter in the paper.

3.1 Semi-Automated Thesaurus Construction

Most of text mining systems applied to patent analysis suffer the influence of the language style and the terminology of the writer; in other terms, when different inventors adopt different terms or expressions to describe the same components and functions, existing text mining application are rarely able to identify the existing semantic link between these concepts.

As described in [6], the authors identify the components of an invention by means of their reference characters, according to the universal patent writing rule which claims that "the same part of an invention appearing in more than one view of the drawing must always be designated by the same reference character, and the same reference character must never be used to designate different parts" [19].

According to this rule, different denominations associated to the same part, must be semantically related at least within the given patent text. Besides, when comparing two different patents, it is necessary to identify if component x of patent X is to be considered the same as component y of patent Y. Chances are that the two components have different names in different patents while referring to the same type of object.

In order to be able to compare components between different patents it is required to build a component denominations thesaurus, which defines concepts as sets of synonyms (synsets) and hierarchical semantic relationships (hyponymy and hypernymy) between those concepts. The proposed approach to semi-automatically build such a thesaurus leverages the extracted components and their alternative denominations, which are then processed through a heuristic of text patterns to identify synonymy and hyponymy relationships.

Table 1 Patent US 5.328.488 "Laser light irradiation apparatus for medical treatment" excerpt from the list of components and their alternative denominations

Component – ref. character	Alternative denominations
Laser light transmissive probe 1	laser light transmissive probe; probe; right side laser light transmissive probe; opposite laser light transmissive probe; laser light penetrating probe; transmissive probe; light transmissive probe; penetrating probe
optical fiber 8	optical fiber; single optical fiber holder;
particle 20	particle; laser light scattering particle; scattering particle
laser light emitting portion 54a	laser light emitting portion; flat emitting portion

3.1.1 Alternative Denominations

In order to provide an unambiguous description of the algorithm for thesaurus construction it is helpful to introduce some formal definitions.

Denomination d_k of a component k is a word, or a set of words, that denotes the component k in the patent text.

Alternative denominations set $A_{k,p} = \{d_1, d_2, \ldots, d_n\}$ of a component k is defined as the set of n denominations referring to the same component k within the patent p (an exemplary set of alternative denominations for a few components of patent US 5.328.488 is shown in Table 1).

The set of all the denominations sets extracted from every component and every patent in a given invention set I is referred as A_I. Finally, it is defined D_I as the set of all the component denominations extracted from I.

3.1.2 Synonymy, Hyponymy and Hypernymy

Synonymy is usually defined as different lexemes with the same meaning leaving open the question of what it means to have the same meaning. If it were to be applied to any context a few words would be true synonyms.

According to [20] the notion of substitutability has been adopted: two lexemes will be considered synonyms if they can be substituted for one another in a sentence without changing either the meaning or the acceptability of the sentence.

So, for the same purpose, it is assumed that two nominal syntagms (either formed by a single word or by several words) are synonyms if they are substitutable in some environment. The environment will be that of an invention set disclosed in a given patent corpus I. Hyponymy is the relation between two lexemes that holds when one lexeme denotes a subclass of the other. A is said to be Hyponym of B, if B denotes a more general class; in this case B is said to be Hypernym of A. Thus, car is a hyponym of vehicle and vehicle is hypernym of car [20]. Hereafter, this kind of relations will be considered as a generalization relation. Hence a thesaurus built according to the algorithm described below will always refer to a single patent corpus I and will be composed of synsets, every synset being a set of nominal syntagms representing component denominations considered synonyms in the context of the said invention set. A synset can be thought as a single concept described by the denominations it contains and representing a common meaning or sense for those denominations.

3.1.3 Co-occurrence Graph

To represent the information about component denominations conveyed by alternative denominations set, it is proposed to use an undirected weighted graph defined as follows: the co-occurrence graph as $G_I = (V, E)$ where $V = \{d_1, d_2 \ldots d_n\}$ is the set of all the component denominations D_I defined above.

Let A_I be the set of all the alternative denominations set found in the invention set I and let $A_{k,p} \in A_r$.

An edge $e \in E$ between node d_i and node d_j exists if $\exists A_{k,p} \in A_I : d_i, d_j \in A_{k,p}$.

Let W be the weight function on G; $W : (E) \rightarrow (\mathbb{N}\mathrm{x}\mathbb{N})$:

the weight of the edge $e \in E$, $W(e) = (w_1, w_2)$ is calculated such that w_1 represents the number of alternative denominations in which d_i and d_j co-occur (in one or more patents of the corpus), and w_2 represents the number of different patents in which this happens.

3.1.4 Component Denominations Thesaurus

According to the definition adopted for the present work mentioned in Sect. 2.3, the thesaurus can be represented as a directed graph, in which nodes represent synsets and directed edges represent generalization relations. As shown below, not only the internal representation of the thesaurus is a graph, but it is possible also to represent it graphically in the user interface, allowing for a clear representation of the conveyed information. The user is also able to interact with the graph to modify it, in order to correct errors of the algorithm or to add or modify relationships that could not be discovered by the system automatically.

In order to build such a thesaurus the following algorithm is applied.

1 *Co-occurrence graph construction*
   Component denominations and alternative denominations sets are extracted from the entire patent corpus I and a co-occurrence graph is built according to the definitions provided above.
2. *Generalization edges transformation*
   The first step to build the final thesaurus graph consists in the transformation of co-occurrence edges in generalization edges. If two co-occurring denominations are in a generalization relation the corresponding edge is transformed in a generalization edge. To identify generalizations a simple heuristic is proposed: if component denomination d_i co-occurs with denomination d_j (there is an edge in the co-occurrence graph) and if $d_i \subset d_j$ then d_i is considered to be hypernym of d_j.
3. *Synsets merging*
   Once every generalization relationship has been transformed, co-occurring denominations are merged in synset nodes. If a merge operation leads to inconsistency (a cycle would be created in the graph) the nodes are not merged and the co-occurrence edge is left for the user to disambiguate. To reduce the number of inconsistencies, the merging algorithm merges edges in an ordered way. Edges are ordered for increasing number of words of the connected nodes and decreasing edge weight. The merging operation starts from the smallest denominations and the highest weights.
4. *User disambiguation*
   In this step the user disambiguates the remaining co-occurrence edges, corrects wrong relations and eventually merges or separates synsets according to his/her specific knowledge of the field.

An exemplary excerpt from a thesaurus construction task is shown in Figs. 1, 2, 3, 4, 5, and 6. The first (Fig. 1) represents the co-occurrence graph (step 1). In Fig. 2 edges representing generalizations have been transformed (step 2); notice the arrow that points to the hyponym.

In Fig. 3 single word co-occurrences have been merged (step 3). It is worth to note that in this trivial example, constituted by a small number of patents and a subset of components, no threshold has been used to merge the nodes; in a general case, synsets can be created by merging only the nodes whose link overcome a minimum number of alternative denominations in which the nodes co-occur and/or a minimum number of patents in which the co-occurrence is found.

In Fig. 4 two words co-occurrences have been merged. Notice that the edge A cannot be merged since there is already a generalization edge connecting the synsets. In

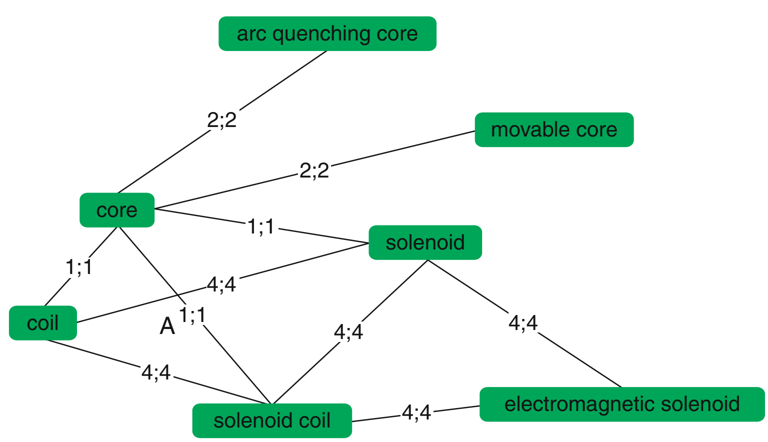
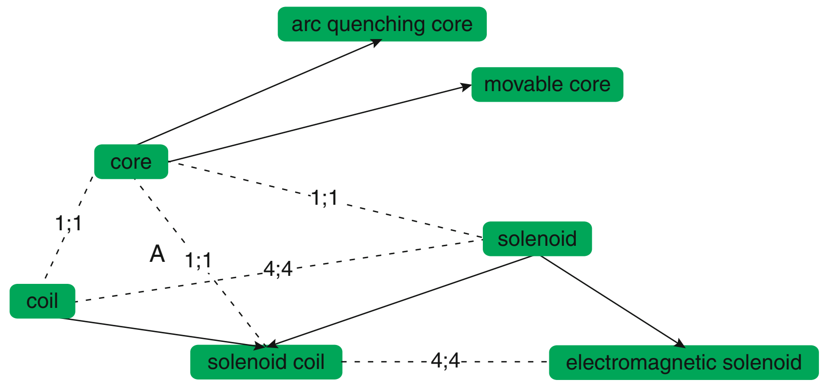


Fig. 1 Edges represent co-occurrence of denominations in alternative denominations set; notice the weight pair on each edge, the *left* number represents the number of alternative denominations set in which the nodes co-occur, the number on the *right* represents the number of patents in which the co-occurrence happens

Fig. 2 Generalizations identification. Generalization relations have been identified and transformed



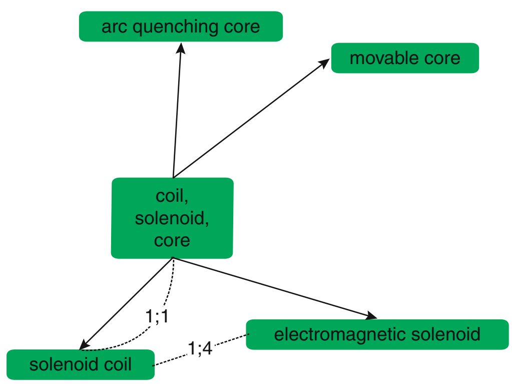


Fig. 3 Denominations merging step 1. Nodes composed of one word have been merged, notice that the edge between (coil, solenoid, core) and (solenoid coil) cannot be merged since there is already a generalization relationship

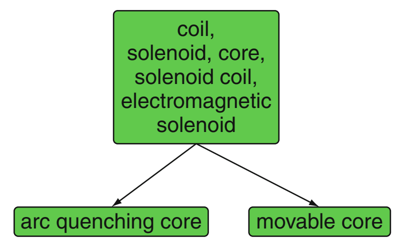


Fig. 5 Disambiguation: the user has chosen to disambiguate the edge eliminating the generalization relation, this leads to the merging of the two nodes

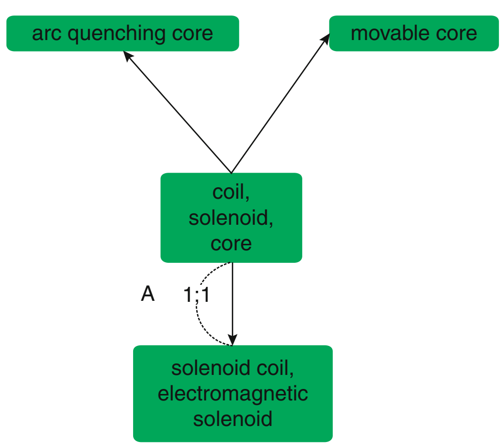


Fig. 4 Denominations merging step 2. Nodes (solenoid coil) and (electromagnetic coil) are merged. The user should disambiguate co-occurrence edge left

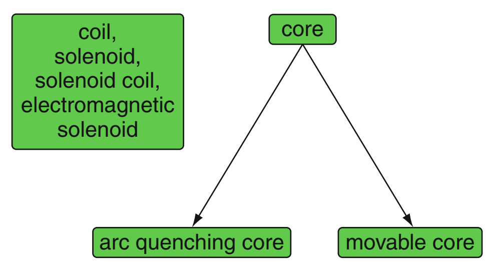


Fig. 6 The final thesaurus. Notice that the user has chosen to manually separate core from the synset (core, coil, solenoid coil, electromagnetic solenoid

Fig. 5 the edge *A* between {coil, solenoid, core} and {solenoid coil, electromagnetic solenoid} has been disambiguated, the expert considers solenoid, solenoid coil, coil and electromagnetic solenoid as synonyms to the extent of this invention set.

In Fig. 6 the final thesaurus is represented. Notice that the expert has chosen to separate {core} from the synset {coil, solenoid coil, solenoid, electromagnetic solenoid)} since it cannot be considered a synonym even to the extent of this inventions set. Notice also that this error could have been easily avoided choosing a higher threshold for merging, since the edge A connecting {core} to the other denominations had a weight of (1,1), this means that this denominations where co-occurring only in one patent.

3.2 *Thesauri Comparison and Field Parameters Identification*

The algorithm described in the previous section allows to build a thesaurus related to a given corpus of patents. It is evident that, due to the adopted criteria, the robustness of the process increases with the uniformity of the corpus contents. In other terms, the reliability of the thesaurus is higher if the analysis is limited to document belonging to the same class and even more if it is focused on a specific sub-class or even a patent group.

Moreover, it is interesting to observe that in most cases the IPC classification, especially for well established products and processes, even if not purposefully, is structured according to a Function-Behavior-Structure hierarchy, such that top level classes distinguish different functions or sets of functions within a given domain, while deeper branches as groups and subgroups are more related to alternative behaviors and structures to deliver the same function. For example, the class D06F covers domestic or laundry devices for washing, rinsing and dry-cleaning textile articles (Function). Within this class the group D06F 23/00 is related to “Washing machines with receptacles, e.g. perforated, having a rotary movement, e.g. oscillatory movement, the receptacle serving both for washing and centrifugally draining” (Behavior). The sub-groups D06F 23/02, D06F 23/04, D06F 23/06 distinguish between “rotating or oscillating about a horizontal/vertical/inclined axis” respectively (Structure).

The main idea of the present work for domain parameter identification, as defined in paragraph 3, is that a comparison between thesauri extracted from specific IPC subgroups, belonging to the same patent class, should highlight common terms mostly related to the main function of the technical system. Besides, it is assumed that the most characterizing differences between thesauri extracted from complementary IPC subgroups are related to the way the function is delivered, i.e. to the behavior and the structure of the related inventions (Fig. 7).By analyzing these attributes from each thesaurus, and more specifically the hyponymy-hypernymy chains in order to extract adjectives and appositions from the hyponyms, it is possible to provide to the user a list of terms closely connected to the features governing the functioning of the system. In facts, as it will be shown in the following section, it is easy to extract from this list of terms a set of relevant domain parameters.

At the current level of development, this last step is still in charge of the user; nevertheless, the speed of the process makes this task much more efficient than a traditional manual investigation of the relevant design parameters.

Since the thesauri extracted according to the algorithm described in Sect. 3.1 can be constituted by hundreds if not thousands of entries, it is suggested to prioritize the analysis by taking into account the terms containing the keywords belonging to the analyzed IPC classes; then, by browsing the thesaurus network through the hypernym/hyponym links, it is possible to build a list of adjectives and appositions from where the user can easily extract relevant technical parameters of the technical field under study.

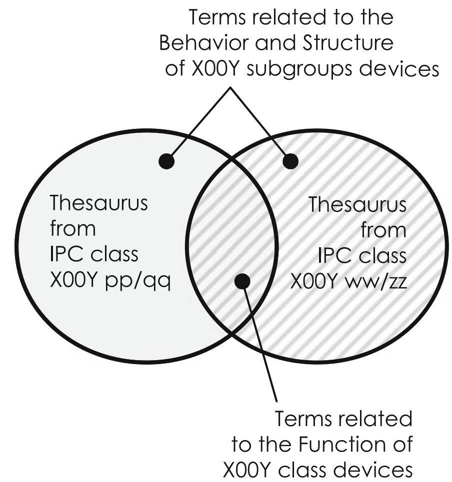


Fig. 7 Comparison of thesauri extracted from IPC groups and subgroups of a same patent class

At the present level of the research, no robust directions have been identified to distinguish, within the domain parameters set, between Evaluation and Control Parameters; therefore the classification is in charge of the patent analyst.

4 Exemplary Application: Technologies for Water Purification

In order to clarify the proposed comparison procedure, this chapter describes an exemplary application in the field of water purification through different technologies.

The most relevant International Patent Class related to this function is the C02F (Treatment of water, waste water, sewage, or sludge), which is subdivided into:

- C02F-1 (Treatment of water, waste water, or sewage);
- C02F-3 (Biological treatment of water, waste water, or sewage);
- C02F-5 (Softening water; Preventing scale; Adding scale preventatives or scale removers to water, e.g. adding sequestering agents);
- C02F-7 (Aeration of stretches of water);
- C02F-9 (Multistep treatment of water, waste water or sewage).

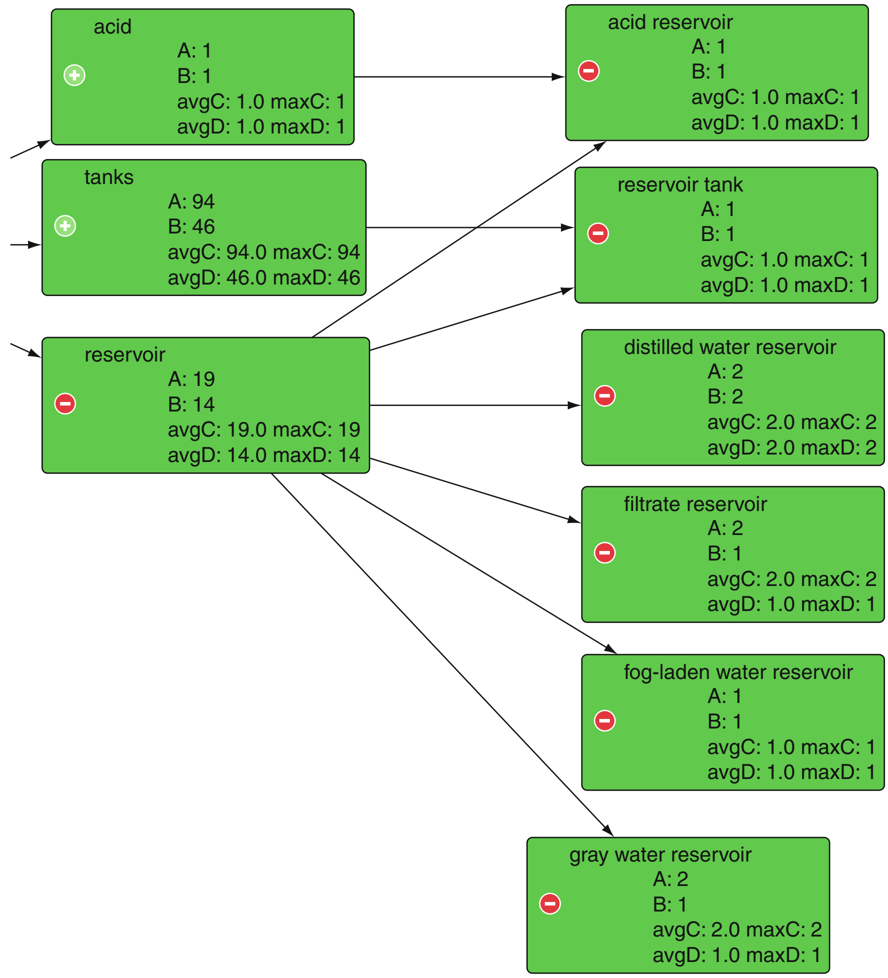


Fig. 8 Excerpt from the thesaurus graph automatically built by processing 150 patents belonging to the class C02F-1/02

As mentioned in Sect. 2.1, each of these classes is further subdivided into full digit classes, related to alternative specific technologies (behaviors) to deliver the main function. For example, the treatment of water (C02F-1) can be operated by:

- Heating (C02F-1/02);
- Freezing (C02F-1/22);
- Flotation (C02F-1/24);
- Sorption (C02F - 1/28);
- Irradiation (C02F-1/30);
- Centrifugal separation (C02F-1/38);
- and others...

A thesaurus has been automatically built for each of these classes through the steps described in Sect. 3.1, by analyzing all the patents granted by the United States Patent Office between 1971 and August 2009 and by the European Patent Office between 1980 and August 2009.

In this case study, the threshold level for automatic acceptance of the semantic relationships (synonymy, hypernymy/hyponymy) have been set as (3, 2), according to the weight definition given in Sect. 3.1. It means that only the semantic links appearing in at least 3 different components and in at least 2 different patents have been stored in the thesaurus. In order to demonstrate the efficiency of the proposed algorithms, neither manual disambiguation, nor manual integration of semantic relationships have been applied. It is clear that a thesaurus improved through the contribution of a subject meta-expert would provide a richer set of information.

An exemplary excerpt from the thesaurus graph related to the class C02F-1/02 (Treatment of water by Heating) is shown in Fig. 8. In this example, each synset is constituted just by one syntagm (single or multiword). The parameters showed in the synset boxes are:

- A = number of components where the synset occurs;
- B = number of patents where the synset occurs;
- C = number of components where each alternative denomination of the synset occurs (average and max value);
- D = number of patents where each alternative denomination of the synset occurs (average and max value).

As stated in the previous section, the hyponyms related to a given term are characterized by attributes that can be associated to parameters which qualify the given term. From the example in Fig. 8, the patent analyst can deduce with no efforts (i.e. without reading any patent document) that reservoirs for water treatment by heating can be classified according to their Control Parameter "content", which can assume the following values:

- acid;
- distillate water;
- filtrate;
- fog-laden;
- gray water.

Indeed, it must be observed that not necessarily the attributes related to the same noun can be assumed as different values of the same parameter. For example, in the class C02F-1/28 the noun "reservoir" has the attribute "solvent", which in fact is a possible value of the parameter "content"; but also "feed" which can be interpreted as a value "feed" of the control parameter "function". Therefore, the interpretation of the parameters must still be done by the patent analyst, as well as the association of the attributes as possible values of each parameter.

Besides, the authors are investigating the possibility to increase the level of automation of the algorithm by connecting the analysis to a general purpose thesaurus as proposed also in [21]. For example, "acid", "water" and "filtrate" share the same direct and indirect hypernyms: "chemical, chemical substance", "material, stuff", "substance", "matter". Thus, the analysis of hypernymy chains might help distinguishing between values related to different parameters

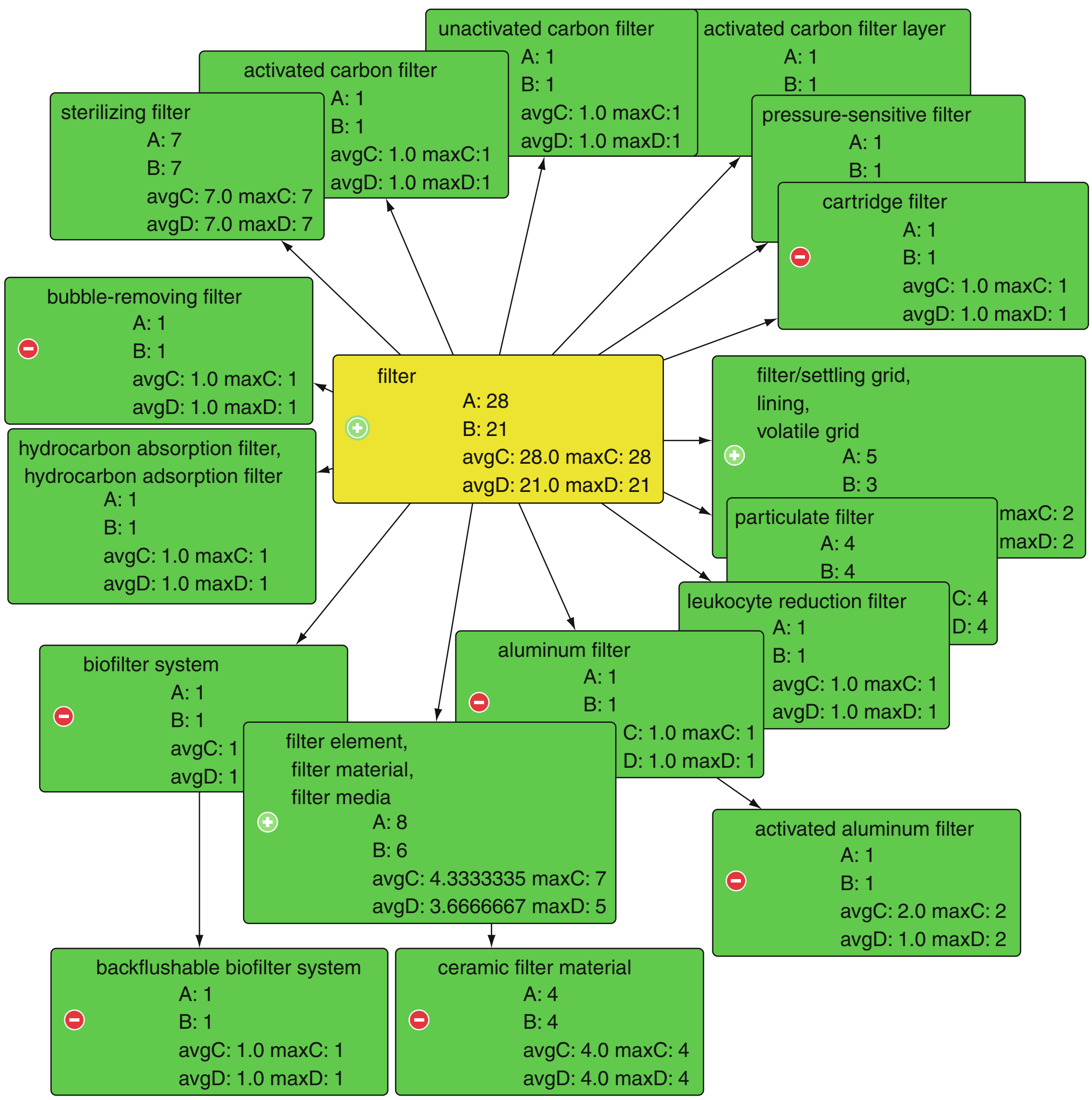


Fig. 9 Excerpt from the thesaurus graph automatically built by processing 341 patents belonging to the class C02F-1/24

and possibly also to identify the categories of the parameters themselves.

As claimed in the previous section, it is interesting to compare the attributes assigned to the same item in alternative technical systems, i.e. the hyponyms sets extracted from complementary patent classes. In facts, the differences help revealing peculiarities and can be proposed to the patent analyst as triggers for identifying the most characteristic technical parameters.

For example, let's consider Figs. 9 and 10 representing the direct hyponyms sets of the item "filter" in the classes C02F-1/24 and C02F-1/28 (water treatment by flotation and by sorption). A technician, even without reading any patent from those classes, can identify with minimal efforts the parameters and values reported in the Tables 2 and 3. Notsurprisingly, flotation systems explicitly cover a wider range of applications as revealed by the evaluation parameters related to the object of the filtering action. Moreover, several action principles have been identified.

Besides, sorption-based systems are characterized by different geometries and properties related to their operating conditions.

By navigating the hypernyms/hyponyms links starting from the keywords extracted by the IPC classes/subclasses titles, it is possible to collect a comprehensive set of parameters and values as a support action for building a model of the domain under analysis.

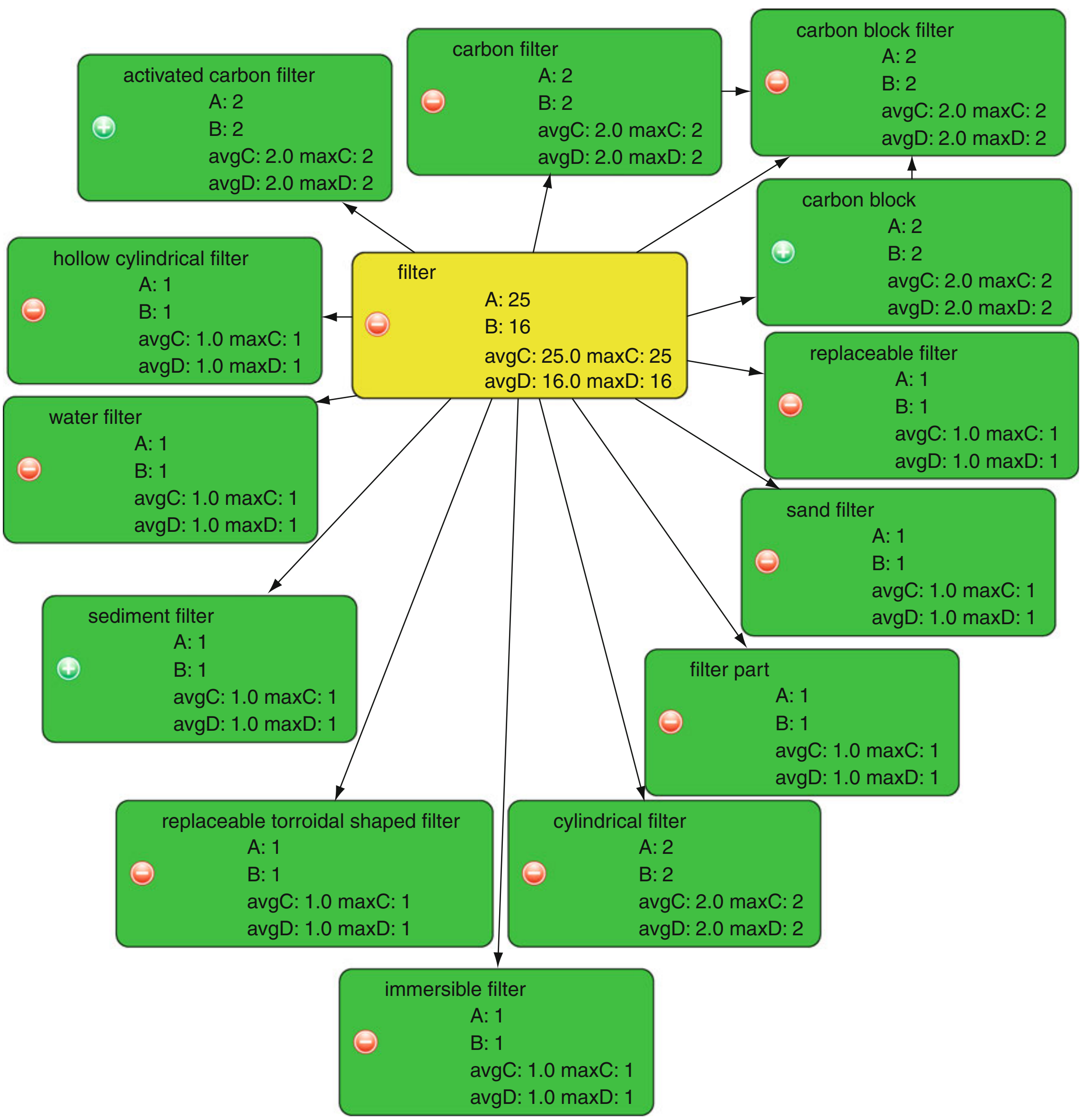


Fig. 10 Excerpt from the thesaurus graph automatically built by processing 150 patents belonging to the class C02F-1/28

Table 2 Exemplary parameters for the item "filter" and related values which can be manually extracted from the hyponym set of Fig. 9

Parameter	Values
Action principle/Filter material	Activated Carbon (filter)
Action principle/Filter material	Unactivated Carbon (filter)
Action principle/Filter material	Aluminum (filter)
Action principle/Filter material	Activated aluminum (filter)
Action principle/Filter material	Ceramic (filter)
Action principle/Filter material	Biofilter
Action principle/Filter material	Absorption/adsorption
Object of filter action	Particulate
Object of filter action	Leukocyte
Object of filter action	Bacteria (Sterilizing)
Object of filter action	Bubble
Object of filter action	Hydrocarbon
Maintenance/Cleanability	Backflushable

Table 3 Exemplary parameters for the item "filter" and related values which can be manually extracted from the hyponym set of Fig. 10

Parameter	Values
Action principle/Filter material	Carbon (filter)
Action principle/Filter material	Activated Carbon (filter)
Action principle/Filter material	Sand (filter)
Shape	Cylindrical
Shape	Hollow cylindrical
Shape	Toroidal
Working Environment	Immersible
Maintenance/Replaceability	Replaceable

5 Conclusions and Further Developments

This present paper addresses the goal of reducing time and efforts necessary to gather domain information from patent analysis. The specific objective is to speed up the identification of domain technical parameters (Evaluation and Control Parameters) relevant for a given field of application. These sets of parameters can be used either for creating a general purpose domain Knowledge Base, or for mapping the key problems to be addressed in a given field of application [2], or even for supporting evolutionary analyses of technical systems [3].

The authors, on the base of their past experiences in the field of patent text mining, are studying the possibility to identify domain technical parameters through the comparison of the thesauri extracted from complementary patent classes. At the current stage of development, the proposed approach allows to provide to the patent analyst a set of attributes for each relevant element of the technical system, from which the extraction of evaluation and control parameters is a quite efficient task, in any case much faster than any approach based on questionnaire to experts or manual patent reading. Nevertheless, the applications performed so far don't allow to estimate the completeness of the domain coverage: it is assumed that the attributes and qualifications reported in the patents belonging to a certain technical field cover all the domain parameters.

The identification of the technical parameters can be further automated by exploiting available information as semantic relationships in general purpose thesauri or the location in the patent text (e.g. parameters extracted from the claims are essentially related to design choices, i.e. control parameters).

Besides, the first attempts to identify also the relationships between the parameters have revealed that further analyses are needed to recognize general patterns to be formalized in terms of algorithmic rules.

The proposed semi-automatic approach to build a thesaurus for a specific patent class and to extract relevant domain parameters has been clarified by means of an example in the field of water treatments, where six alternative technologies have been analyzed. The promising results obtained so far suggest to investigate with further case studies the validity of the proposed algorithms and the opportunities for further development.

Acknowledgments The authors would like to thank Niccolò Becattini and Walter D'Anna from Politecnico di Milano for their contribution to patents search and analysis.

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Knowledge Extraction from Patent: Achievements and Open Problems. A Multidisciplinary Approach to Find Functions

D. Russo

Abstract Patents are an increasingly important source of technological intelligence that companies can use to gain strategic advantage. Public databases, such as Espacenet, offer for free, available over the internet, some millions of documents with constant format and always updated. So, the answer to most of our technical questions depends on how we are able to extract crucial information from patent corpus and translate them into knowledge. A general overview on universal tools for knowledge management (bibliometric, text mining, semantic) is proposed, with the aim to highlight what problems have already been overcome and what still needs to be done, especially for TRIZ users who want to identify technical features in a text.

Keywords Data Mining · Ontology · TRIZ · FBS · ENV model

1 Introduction

Patent database has grown becoming one of the central knowledge sources of mankind, maintained by millions of contributions per year. The challenge is to manage this gigantic source of knowledge by extracting structured information from patent text and by making this information automatically accessible by means of computers in an effective model of representation.

Much of this information is expressed in natural language texts that need efficient tools in order to be extracted and collaborative work from several heterogeneous fields such as computational linguistics, informatics, engineering, psychology.

We have tried to simplify the approaches for patent analysis tools, by classifying them into just 3 categories: a bibliometric approach, text mining and semantic based searches.

Techniques for patent analysis have evolved only recently and have not yet reached maturity.

Regardless of the approach, limits are obvious and potentialities not fully explored. In the second section an overview about patent analysis tools is presented, according to a "problem – partial solutions" approach. Ontologies and their role for patent analysis, and some personal suggestions to choose the most advisable for who is working on TRIZ-based feature extraction are introduced in the third section [1–3]. In the fourth section some of such ontologies as OTSM-TRIZ [4] and FBS model framework by J. Gero [5] are briefly shown.

But tools are insufficient to cover all kind of information extraction activities, and knowledge acquisition. Thus, an introduction of ontologies is proposed together with a detailed investigation of lexical and semantic relationships. The multidisciplinary integration of tools and approaches is shown by an exemplary application dealing with "how to set a function-based search". Design ontologies (as Function-Behaviour-Structure by J. Gero), and TRIZ ontologies (such as ENV model from OTSM) are merged and combined with linguistic techniques and Knowledge management tools in order to overcome linguistic problem hiding a function in traditional function based patent searches.

Finally in the last section we propose to face a still open issue, relating to the function based search, showing how function could be extracted by overcoming linguistic problems by means of integration of a plurality of selected ontologies, and suitable data mining techniques.

2 Patent Analysis Tools

2.1 Bibliometric Tool

Usually, traditional patent analysis utilizes bibliometric data. Bibliometrics is defined as the measurements of texts and information, which helps to explore, organize and

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analyze large amounts of historical data so that researchers can identify 'hidden patterns' to support their decision-making [6].

Bibliometric software for patent analysis have been proposed in the last years thanks to the ability to provide conventional patent maps, easy to understand and simple to develop. Using only a small part of information of a patent however (i.e. authors, affiliations, technology field, cluster, citations and so on), limitations in terms of their explanatory and creative capacity are evident and the scope of analysis and the richness of information are limited [7].

This could be the reason why in literature it is difficult to find TRIZ-oriented patent analysis exclusively based on bibliometric techniques. It is possible to believe however, that in the future bibliometric applications will continue to grow, also as auxiliary tools to the main activities of knowledge extraction (i.e. using a patent citation as a means for key-patents identification) and for a more powerful application: the use of IPC cluster (international patent classification) as a source for setting linguistic domain, full of keywords independent of the specific language of both the documents retrieved and the user [8, 9].

Every patent, behind its IPC code, contains a treasure of structured keywords and expression, already filtered by patent office specialists. Language of IPC description reflects typical jargon of every specific technological domain, and could be used as a support to build conceptual thesauri.

2.2 Data Mining Tool

Much more articulate and complex approaches to the patent analysis are those based on Data Mining.

Data mining is the process of extracting patterns from data and comprises:

- Classification – Arranges the data into predefined groups. Common algorithms include Nearest neighbor, Naive Bayes classifier and Neural network.
- Clustering – It is like classification but the groups are not predefined, so that the algorithm will try to group similar items together.
- Regression – Attempts to find a function which models the data with the smallest error. A common method is to use Genetic Programming.
- Association rule learning

The recent extraordinary development of DM techniques (text mining in particular) has extended the horizon of research to the unstructured textual data and, therefore, the whole text of a patent document.

Applying TM in patent analysis allows us to handle large volumes of patent documents and extracting some meaningful implications from textual data.

Applications of text mining techniques to assist the task of patent analysis and patent mapping are countless [10], both for TRIZ and not TRIZ experts.

One of the most popular applications of TM techniques is to monitor the significant-frequent terms by means of classical methods such as TF/IDF traditional term frequency (TF) and inverse document frequency (IDF) in order to improve patent retrieval activity [11].

Text mining is also used to transform patent documents into structured data to forecast technology opportunities identifying keyword vectors [7, 12]. In other cases, keywords combined with artificial neural networks are used for pattern recognition and document classification [13], or for quantifying and formalizing product aspects [14].

This list is not exhaustive but regardless of the purpose, and why text mining is used, the results of these approaches are strongly influenced by the fact that assignees may use different terms in different fields to describe the same thing.

The reasons why they use different terminologies are due to:(1) lack of standard keywords: experts in different domains use dissimilar words; (2) lack of standard name of a developing technology; (3) incorrect translation: there is not a standard translation among different languages; (4) some inventors and assignees don't want to be completely transparent even when they choose to file patents. [11]; (5) the claims, which precisely specify the boundary of the invention and thus are valuable for TM, are generally written in arcane legalese so that it is difficult to extract technical meanings [7].

To partially overcome language barriers and to generate more relevant results, domain thesaurus is proposed.

A thesaurus is a hierarchical structure which classifies domain terminologies into different concepts. It is very common that the domain-specific terms cannot be covered by common dictionaries. Therefore a domain thesaurus is needed for machines to process specific domain corpus to understand the meaning of these terminologies.

2.3 Semantic Search

To conclude the overview of available tools for textual management the Syntactic Analysis is introduced.

Syntactic analysis consists in modeling the structure of a sentence, assigning to the sentence itself the most likely interpretation. The fundamental idea behind syntactic parsing is that groups of words may behave as a single unit or phrase (i.e. noun-phrases), called constituent. Generating constituents from a sentence allows us to model constituent facts (concepts).

By means of a syntactic parser, for example, TRIZ users can break up a text into SAO triads (Noun phrase – Verb Phrase – Noun Phrase), interesting for those looking for problem reformulation and technology transfer [15]. More specifically TRIZ software uses syntactic parsers to translate functional relationships into semantic relationships within a problem reformulation in natural language query patent [16]. Semantic search helps to disambiguate queries, to use natural languages instead of Boolean search and to set research according to a function oriented approach [17].

Even if semantic search can nowadays be considered the most advanced tool for information extraction, results cannot be considered satisfactory if compared with potentialities, especially for clustering and content analysis.

The history of SAO triads extraction from Patent is characterized by a good presence of users coming from Triz community, integrating it in software for problem solving activities [Goldfire Innovator], software extracting a functional model of an invention (PatAnalyzer by Cascini), and platform to support invention process [18].

But the logic of SAO extraction could provide good results only if the pertinent semantic domain was well defined.

Ontology is the answer to these limitations but it can do much more.

3 Ontology

Regarding to the word "Ontology" many meanings are implied; here a list of pragmatic definition are shown:

> Ontology is a common vocabulary, with a meaning for every term that everyone agrees [19]

> Ontology identifies the basic terms and relations of a given domain, thus defining the vocabulary, and rules for combining those words and that relationship, going beyond the vocabulary itself [20]

> Ontology is a hierarchically structured set of terms to describe a domain that can be used as a foundation for a knowledge base [21]

> Ontology is a mean for describing explicitly the conceptualization behind the knowledge represented in this base of knowledge [22]

According to the definition of ontology and the meaning of conceptualization, we can deduce that an ontology consists of general terms that express the main categories in which the world is organized (such as thing, entity, substance, person, physical object, etc...) or specific terms describing a particular domain of a specific application (domain ontologies). Ontology is also the definition of a term and the relationship between words.

Hence, the ontology is used for:

- common lexicon: the description of a target domain requires a lexicon shared among people involved. A major contribution is given by terms in an ontology;
- explanation of what was left implicit in all human activities: there are explicit assumptions and implicit assumptions (i.e. the definition of common terms, relationships and constraints between them, different points of view in phenomena interpretation);
- knowledge structuring: a well established concepts/vocabulary are required, by which people describe phenomena, theories, etc;
- an ontology, therefore, provides the backbone of the systematization of knowledge;
- a meta-model: a model is generally an abstraction of a real object.

In the next paragraph a set of ontologies, conceived for those who want to extract TRIZ features from patents, will be suggested.

4 A Set of Selected Ontologies

Among the enormous number of available ontologies for extraction of TRIZ features from patents, it was decided to recommend two in particular: ENV model and FBS model.

Versatility of these ontologies was checked in the past by the author in various applications: for automatic contradiction extraction, to find invention peculiarities, to conduct supervised technological benchmarking, to build a network of inventive solutions and finally to identify innovative technological opportunities (Russo 2007–2009).

4.1 ENV Model

The ENV (Element, Name of the property, Value of the property) model is a universal model proposed in OTSM-TRIZ [23] for describing a system or a problem, an inventive solution. The structure has been derived from a well known model in Artificial Intelligence Object-Attribute-Value (SAO).

Element (E) is any kind of item in the system under analysis (both material and immaterial). The Name of the property N indicates any characteristic, feature, variable which can be associated to the element E.

Whatever is the property, it must have at least two possible values (V), i.e. the element E can assume at least two possible states distinguished by different values V1 and V2 of the property P (Fig. 1).

Fig. 1 An example of ENV application for a motion description: "a tool moving an object", is a tool that changes the value of the object's (E) speed (N) from zero (V1) to a certain value (V2) measured in km/h

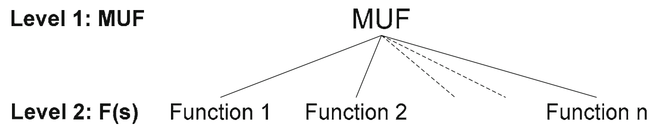

Fig. 2 Function decomposition: each branch represents a different way, expressed by an action, in order to obtain the same result of the given main useful action

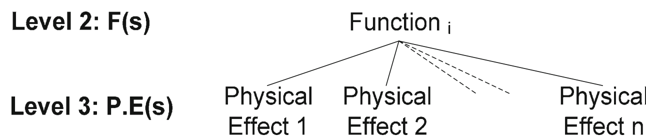

Fig. 3 Level Physical classification: every function is decomposed in a list of physical/chemical effect by means the related function can be provided

4.2 FBS Model

J.S. Gero proposes the (FBS) Function Behavior Structure model in order to describe the design process. Variables and design choices are grouped by three classes of variables describing different aspects of a design object:

– Function (F): "is the motivation for Technical System existence", i.e. what it is for.
– Behaviour (B): "sequential changes of objects state governed by the Laws of Nature, is the link between Function and Structure. Different behaviours can produce the same Function, as well as different Structures can be characterized by the same Behavior", i.e. what it does.
– Structure (S): describes the components of the object and their relationships, i.e. what it is.

4.3 Alternative FBS Model

This chapter presents how the function–behaviour–structure (FBS) ontology can be used to represent processes despite its original focus on representing objects. The FBS ontology provides a uniform framework for classifying knowledge, and is suitable to include higher level semantics in its representation. Knowledge Classification is already based on 3 levels: Function, Physical/chemical Effect and Design Parameter. The new operative definitions follow:

– Function(s) level: this level is based on the network of alternative functions, by which it is possible to obtain the same objective. This level is built by identifying the Main

Useful Function of the system: the motivation of the existence of the system. Such a level is completed by generating all possible functional variants (alternative functions) by which it is possible to obtain the same product/result of the main useful function. For example the main useful action for a nutcracker is to crack nutshell. Possible functional variants are: to cut, to dissolve, to pierce, to explode, to abrade the nutshell (Fig. 2).

– Physical/chemical Effect(s) level: every function can be decomposed according to different principles/phenomena suitable to provide it. "Physical/chemical effects can be described quantitatively by means of the physical laws governing the physical quantities involved" (Fig. 3).

In order to systematize this activity, actual TRIZ DBs of effects have been merged to offer a reference framework; fields, substances, and properties are organized by groups (mechanical, acoustic, thermal, chemical, electric, magnetic, electromagnetic, biological), and for each, a list of specific phenomena is suggested.

For example (Table 1):

– Design Parameter(s) level: the knowledge mapped at this level is classified on the base of parameters on which the designer can apply modifications, i.e. design choices. In order to better classify and specify all the workability directions and the design parameters taken into account, a further classification of this level is provided. Such a classification is based on the depth of detail/specificity level. Thus, the design parameters are divided into three different types, as following:

Type 1: parameters/variables concerning the interaction between the selected object and the other elements of the system.
Type 2: parameters/variables describing the object regardless of the context (system in which it is placed) and concerning design choices for manufacturing and dimensioning.
Type 3: parameters/variables concerning physical properties of the object, i.e. constituting material, physical state, density, etc (Fig. 4).

Table 1 An example of field classification from Db of effects by Zinovy Royzen- from book of TOP-TRIZ course

Basic mechanical field:
- pressure
- delta pressure
- compression force
- tension force
- torque
- gravitational force
  - buoyancy force
- forces of motion, velocity, momentum, torque, potential energy
  - straight line motion
  - projectile motion
  - rotation motion
  - circular motion
  - Coriolis force
  - jet force
- force of kinetic friction
- force of static friction
- restoring force
- Oscillatory motion, pendulum, vibration
  - driven oscillations
  - resonance
  - standing waves
  - infra sound waves
  - sound waves
  - ultrasound waves
- fluid motion
  - steady flow
  - Bernoulli effect
  - unsteady flow
- impulsive force (collision)
- shock waves
- surface forces
- surface tension
- capillary attraction
- wetting
- osmosis
- diffusion
- absorption/adsorption
- Van de Waals force
- mechanical force differential

. . ..

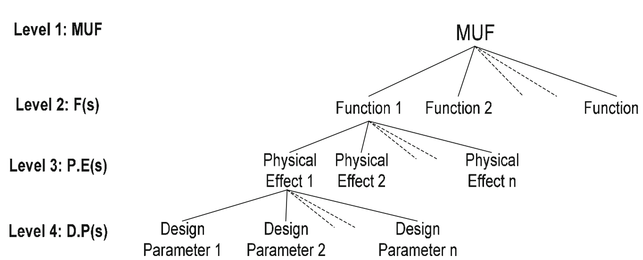

Fig. 4 Level structure classification: the ultimate leaf of each branch contains the structure using the specific phenomenon by which function is provided

Rather than exploring into details the mechanism how, depending on the previous aim, ontologies could be integrated in different ways with other Knowledge management tools, a case study dealing with a very universal problem, (still not completely resolved) is proposed in the next section: "How to extract knowledge about a given function, defining the right meaning at the right level of detail (using, of course, a combination of text mining, semantic search and ontology)."

5 Function Based Search: A Still Open Problem

Working on function it is a crucial point for extracting every kind of TRIZ features from patent documents.

Dozens of attempts are reported in literature about how to set an accurate set of verbs to identify Inventive principles. Such verbs are used as keywords constituting queries during information retrieval works.

Others function oriented searches, based for example on SAO extraction, are numerous but in general they cannot offer good results without an accurate definition of all the keywords related to the given function. For these reasons, usually, it is suggested to find the best expert in the identified leading area and support these activities using professional DBs.

Whatever activity is proposed, identifying and managing the right keywords to find patents, dealing with a given function, is a task requiring sensitivity and experience.

Indeed searching a function doesn't only mean to find synonyms (verbs with the analogous meaning that, substituted to the given one in the same context, doesn't change the right value of the proposition) but it involves to explore a variety of linguistic forms and relationships among words in order to throw up the implicit knowledge function related.

The complexity of this work is due to 3 reasons at least:

1. every inventor has his own style, and the same concept, represented by a given verb, could be expressed at a more abstract level of detail (by means of a less technical lexicon), or at a deeper level (by a very specific jargon);
2. people coming up from different areas (technical field, geographical, cultural background, etc.) use different expressions and so different keywords to express the same concept;
3. a concept represented by an action can be expressed also by other syntactic categories. Let see the case of "an object moving to . . ." . The verb "to move" can be found in a text under different forms as :

- a functional verbal form (an object moves to. . .)
- an adjective (a movable object. . .)
- an adverbial form (the object is movably mounted. . .)
- a paraphrase (an object able to move. . .)

– a noun (move, motion,...) indicating the result of the action on the object.

This incomplete list could be expanded but it is already sufficient to show how many things can affect the outcome. Since problems are a combination of linguistic and technical problems, also solutions will be a combination of linguistic and technical approaches.

In the next paragraph some linguistic definitions and technical ontologies are proposed to solve the problem.

5.1 *Using Dictionaries and Conceptual Thesauri*

Classical dictionaries are undoubtedly the main source to keep suggested words, both in the definition and in synonyms list of the given verb. By these words the initial query can be enlarged including similar terms. The way to combine similar terms can be provided by several tools (better if semantically) but always query expansion is done combining such a words by Boolean operators.

For example using Collins Thesaurus of the English Language and searching a definition of « to move », over 100 alternatives are suggested. Most of them however, don't belong to the same domain and they have to be manually killed (Table 2).

Table 2 A list of synonyms from Collins thesaurus dictionary

From collins thesaurus of the english language – 2002
Verb: TO MOVE
1. transfer, change, carry, transport, switch, shift,
2. go, walk, march, advance, progress, shift, proceed, stir, budge, make a move, change position
3. take action, act, do something, take steps, take the initiative, make a move, get moving, take measures
4. relocate, leave, remove, quit, go away, migrate, emigrate, move house, flit, decamp, up sticks, pack your bags, change residence
5. change, shift, convert, transform, alter, diversify
6. progress, develop, advance, make progress, make headway.
7. change your mind, change, shift, reconsider, budge, climb down, do a U-turn, back-pedal, do an about-turn, change your tune, do an about face
8. drive, lead, cause, influence, persuade, push, shift, inspire, prompt, stimulate, motivate, induce, shove, activate, propel, rouse, prod, incite, impel, drive stop, prevent, discourage, deter, dissuade
9. touch, affect, excite, impress, stir, agitate, disquiet, make an impression on, tug at your heartstrings (often facetious)
10. circulate, mix, associate, go round, hang out, socialize, keep company, fraternize
11. propose, suggest, urge, recommend, request, advocate, submit, put forward

Table 3 Some examples of semantic categories of the verb concepts from WordNet 2.0

Name	Contents (verbs of)
Body	grooming, dressing and bodily care
Change	change of size, temperature, intensity
Cognition	thinking, judging, analyzing, doubting, etc.
Communication	telling, asking, ordering, singing, etc.
Competition	fighting, athletic activities, etc.
Consumption	eating and drinking
Contact	touching, hitting, tying, digging, etc.
Creation	sewing, baking, painting, performing, etc.
Emotion	feeling
Motion	walking, flying, swimming
Perception	seeing, hearing, feeling, etc.
Possession	buying, selling, owning and transfer
Social	political and social activities and events
Stative	being, having, spatial relations
Weather	raining, snowing, thawing, thundering, etc.

Table 4 A selected list of synonyms filtered by the most relevant synsets from Wordnet 3.0

From Wordnet search – 3.0
Verb: TO MOVE
<verb.motion>S:
1. (v) travel, go, move, locomote (change location; move, travel, or proceed, also metaphorically)
2. (v) move, displace (cause to move or shift into a new position or place, both in a concrete and in an abstract sense)
3. (v) move (move so as to change position, perform a non translational motion)
4. (v) move (change residence, affiliation, or place of employment)
Verb: TO MOVE
<noun.act>S:
5. (n) move (the act of deciding to do something)
6. (n) move, relocation (the act of changing your residence or place of business)
7. (n) motion, movement, move, motility (a change of position that does not entail a change of location)
8. (n) motion, movement, move (the act of changing location from one place to another)
9. (n) move ((game) a player's turn to take some action permitted by the rules of the game)

A Semantic approach instead, can distinguish the domain and filter exclusively the alternatives linked to the motion domain.

Semantic dictionaries such as WordNet 3.0, offers an exhaustive list of synonyms and also other related syntactic forms as shown below (Tables 3 and 4).

Now, once a function is given, a rich set of keywords is easily at disposal for Boolean combination without introducing too much noise into search results.

To get even more results it is needed to enlarge the set of synonyms used for queries to those related to the domain of the given function. In other terms a conceptual thesaurus is requested: a dictionary with words (verbs, noun, adjectives, adverbs etc.) describing technological area related of the given word.

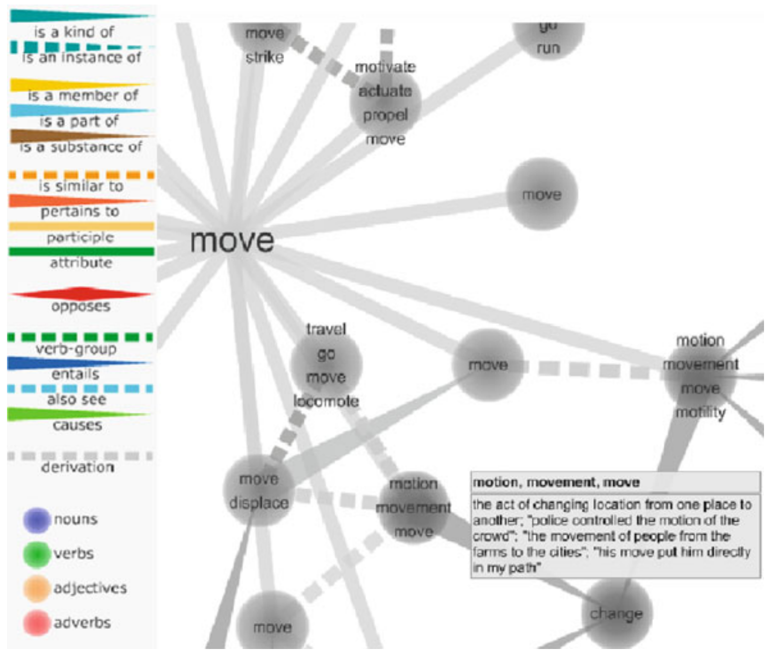

Fig. 5 Screenshot of a search about to move taken from the online graphical dictionary visuword_ http://www.visuwords.com

Commercial software for building automatic conceptual thesauri, unfortunately, is not reliable yet, but there are some, like Visuword, that can still give some help. A picture taken from Visuword is shown in the following figure.

Conceptual thesauri can offer a set of terms to be added by Boolean operators to the initial query (or to that already expanded by synonyms) (Fig. 5).

5.2 Using Patent Classification as a Source for Contextual Synonyms Extraction

While waiting a new generation of conceptual thesauri, another way to generate contextual synonyms has been identified. For the author just a linguistic approach it will never cover all technical expression, especially those dealing with a very specific jargon. There are a lot of technical areas from where an author can draw terms to describe his invention that no dictionaries could entirely cover. In order to overcome this problem and nevertheless to build reliable thesauri, patent classification lists (as IPC, ECLA, Us classification) are taken into account.

Each full digits Patent class defines a certain technological area. Although not always true, a patent class circumscribes in most cases a typical jargon. Words extracted from these Pat-Class definitions can be used as representative keywords to start building a thesaurus. From those keywords, all strategies, already presented in the previous sections can be exploited and integrated in.

Indeed, browsing semantically inside Pat-classes it is possible to define not obvious links among clue terms (verbs, adverbs, nouns and adjectives), having similar meaning exclusively in that specific context.

The verbs *to cut* and *to heat*, for example: no dictionary could connect them as synonyms but they can be considered synonyms in a specific context as laser cutting.

5.3 Using Verbs Classification as NIST

Unfortunately patent writers don't use always specific language, but sometimes they rather prefer a more general language to better claim the idea of the patent.

In order to find a system to represent any form of abstraction of the given function some attempts are ongoing checking a list of verbs prepared by the National institute of standards and technology U.S. department of commerce (NIST).

Instead of use a linguistic approach it is suggested to move to a more technical approach.

NIST developed a hierarchical taxonomy following the approach by Pahl and Beitz. The NIST taxonomy provides a set of terms that are atomic, but also generic enough to allow modeling of a wide range of engineering systems.

NIST list of verbs is classified in three levels with increasing degree of specification. Once fixed the given action, a similar verb has to be chosen from those in the list. Looking at the hierarchical classification it is sometimes possible to go back to the more abstract forms of language. Below an

Table 5 An example of "branch"-function decomposition taken from NIST – A functional basis for engineering design

Primary	Secondary	Tertiary	Correspondents
Branch	Separate		Isolate, sever, disjoin
		Divide	Detach, isolate, release, sort, split, disconnect, subtract
		Extract	Refine, filter, purify, percolate, strain, clear
		Remove	Cut, drill, lathe, polish, sand
Overall increasing degree of specification – >			

example of a hierarchical organization is presented dealing with the verb "to branch" (Table 5).

5.4 Using Lexical and Semantic Relationships

In the previous paragraphs, different ways to collect synonyms are presented. Best dictionaries provide a plurality of definitions already classified by domain; they provide synonyms and sometimes some other related term. Since this is not enough, it was considered useful to provide a detailed set of the most important lexical relationships for aiding patent information retrieval. The aim is to provide the minimal needed linguistic knowledge to complete by ourselves the set of keywords given by dictionaries and thesauri.

A good Thesaurus doesn't contain only synonyms but also:

– *Antonyms*, that are words with opposite or nearly opposite meanings. For example: increase and decrease, dead and alive, short and tall. The term antonym has also been commonly used as a term that is synonymous with opposite; however, the term also has other more restricted meanings. Antonym of a word "x" is usually "not x" but sometimes that could not be true. Rich and pour are antonyms but "not rich" couldn't mean to be pour.
– *Pertainym*; this relationship doesn't belong to verbs but only to adjective or indirectly to adverbs. There are adjectives defined by "meaning relating to or pertaining to" and they don't have antonyms. An adjective of pertainym can be related to a noun or another adjective of this type.

Here, a set of semantic relationships follows.

– *Hypernyms* and *hyponyms* are words that refer to a general category and a specific instance of that category respectively. For example, vehicle is a hypernym of car, and car is a hyponym of vehicle. Hypernym/hyponym pairs can be found in text corpora by looking for certain syntactic patterns.
– *Meronymy* is a semantic relation used in linguistics. A meronym denotes a constituent part of, or a member of something. That is,

  X is a meronym of Y if Xs are parts of Y(s), or
  X is a meronym of Y if Xs are members of Y(s).

– *Holonymy* is a semantic relation. Holonymy defines the relationship between a term denoting the whole and a term denoting a part of, or a member of, the whole. That is,

  'X' is a holonym of 'Y' if Ys are parts of Xs, or
  'X' is a holonym of 'Y' if Ys are members of Xs.

  For example, 'tree' is a holonym of 'bark', 'trunk' and 'limb.'
– *Entailment,* is the relationship between two sentences where the truth of one (A) requires the truth of the other (B).

  A verb X entails Y, if X cannot be provided without Y is provided.

  Entailment is a unidirectional relation, if X entails Y, the contrary isn't true, but it doesn't happen if two verbs are synonyms. For example, the action of preparing a nut consists of a first stage of cracking shell and extracting nut. This relationship could be used to decompose the given function.
– *Troponimy*, it is a particular entail relationship;

  if X is troponym of Y, thus X entails also Y.
  "If to limp is troponym of to walk, I can't limp without walking, so to limp entails to walk."

– *Causal relation*, is similar to entailment but without time aspects.

  If X causes Y, X also entails Y, where X is a verb indicating the cause or the activity related to the verb Y
  Entail and "cause to" are unidirectional: "Feeding causes that a person eats, the fact that a person is eating does not mean that someone is giving something to eat."

5.5 Using Ontologies

Even if we were able to define every kind of linguistic relationship, to achieve the goal could be difficult. This is because in most cases patents aren't written in a functional language. For such a reason only a radically different approach can recognize a specific action in a text without it is described as a verb.

ENV model pushes user to consider a function from another point of view, not only as a combination of words related to the action but as a mean to change parameters of an element.

Every system can be reduced to a minimal set of elements constituting the system and conceived in order to provide a function onto an object. Due to this function the object becomes a product. This transformation can be described as a triad SAO like "to change, or to increase, or to decrease or to maintain the value of a feature of an element of the system". Thus the concept of function can be recognized just looking at specific set of verbs in combination with technical parameters.

Research exclusively based on linguistic relations around a given word is now enlarged to new information dealing with the object and with its transformation.

FBS ontology helps to find a function when the given function doesn't compare in a text but it is decomposed by different actions, such as in case of relationships of "entailment" and "causality".

It is also used when the given function doesn't appear at all in the text but it is substituted by means of

- its physical principle (Centrifugal force implies the action of twisting, differential pressure instead of to explode)
- its structure by means of a specific design parameter (a wavelength of 260 nm instead of to sterilize, a wavelength from 315 to 400 nm instead of to bronze),
- a representative technological tool (using a knife substitutes the action of cutting, X-ray instead of scanning, microwave instead of heating).

In some cases it is easier to find specific word dealing with the structure or with a specific phenomenon or a physical principle rather than looking for an action that could be missing or too general to be found (implicit knowledge). FBS offers the way to change strategy or to integrate it into the traditional function based queries (Table 6).

Suggested ontologies don't have to be considered as alternatives to others linguistic approaches but just an additional support to make more complete and reliable powerful patent searches for Triz features.

All different suggestions can finally be used to build a query expansion algorithm that opportunely combining linguistic resources with design and TRIZ ontologies as in particular:

- terms taken from synonyms/antonyms/and other lexical relationships of the given verb
- terms coming from conceptual thesauri and Patent Classification
- verbs at different detail level
- verbs related to the physical principle by means a given action is provided
- verbs generated by modifying design parameters.
- verbs related with the object's transformation
- etc.

The author is now experimenting all these suggestions on a new algorithm for extracting and organizing patent knowledge called KOM Module, Knowledge Organizing Module [24, 25], now under software implementation.

6 Conclusion

Today, working on patent is often a pioneering activity. Indeed, despite the huge amount of information contained in several millions of technological inventions, only very few knowledge is actually retrievable.

This work proposes a reflective reasoning about the main problems and best suggested strategies and tools dealing with "how to automatically extract functions from a patent text."

Table 6 In the US4358467 the main function is to cut the shell but instead of it writer prefers to use both very general terms as removing, and contextual synonyms of laser cutting as to burn. The terms in bold are those automatically selected by KOM during the expansion of the query

Patent number #	FBS
US4358467 – [. . .] The removal of shells from hard shelled nuts, particularly macadamia nuts, is accomplished by rotating the nut in the path of a high power cw *laser beam*, such as a CO_2 *laser beam*, so as to *burn* a path around the shell which separates the shell into parts which can readily be removed from the nut.	F: to cut shell B: Thermal field: to heat/to burn S: Laser/laser beam/CO_2 laser
JP56001849 –[. . .] In the method, the coffee beans are suspended in a liquid and then the suspension is irradiated by means of *ultrasound* with a *frequency* of between 13 and 100 kHz, with sufficient energy to give rise to *cavitation phenomena.*	F: to consume shell B: Mechanical field: cavitation S: Ultrasound/frequency/hertz/
CN 86205713 – The utility model discloses a husking device for hard and crisp husk nuts of pine nut, acorn, hazelnut, sunflower seed, etc. The machine is designed by applying the *collision theory*, which mainly comprises a hopper, a husking breaking unit, a kernel dividing unit, a husk out groove and a kernel out groove	F: to brake shell B: mechanical field: collision/hit S: hammer/. . .
FR2607670 A1 – The subject of the invention is a method for opening shellfish and the apparatus for implementing the method. It is composed of a frame 12 which can receive a plate 2 on which the shellfish are arranged, a means acting as a lid 9 forms, in a leak tight manner, the space 8 which is subjected to vigorous *depressurization* and/or ultrasound either through a *vacuum* pump 6 or by an *emitter* 13	F: to channel B: mechanical field: differential pressure S: vacuum

This chapter presents the state of the art of the most important Knowledge management and text mining tools, focusing on how benefits can be brought using each of these tools and what problems still remain unsolved.

The author's experience in patent processing has been developed with the aim of extracting design features (TRIZ in particular) from patents. Just some examples about it are proposed in this chapter showing why good results are not achievable simply using one TM tool, even the most advanced [26–29].

Every source of information is an essential resource; for that reason it is suggested to exploit inside the patent all linguistic aspects (as lexical and semantic relationships, Boolean and semantic search approaches) by means of most advanced dedicated instruments (i.e. dictionaries, conceptual thesauri, linguistics browsers, catalogs of functional verbs as NIST, etc.) and integrate them with knowledge contained outside the patent both in a specific link to the patent classification index and more generally from conceptual design ontologies (i.e. a functional design approach as FBS or ENV model).

Such a combination of tools has been applied to some exemplary cases in order to show how to extract implicit "functions" from patent text. Cases studies and author's suggestions aren't shown in all details but they are proposed as a source of information for others researching the same field.

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Acquisition of Evolution Oriented Knowledge from Patent Texts

F. Rousselot, C. Zanni-Merk, and D. Cavallucci

Abstract In this chapter, we present an approach to knowledge acquisition from patents based on our own inventive design methodology. This methodology, based on TRIZ, extends its practice to the resolution of complex problems. We have proposed an ontology of all the concepts and models used in our approach. An operative process easing knowledge acquisition, useful to the experts practicing inventive design, is based on this ontology.

Keywords Knowledge acquisition · Patent · Invention · Inventive design · TRIZ

1 Introduction

Patent analysis done by experts requires a considerable effort and any approach tending to facilitate these tasks is welcome.

Most of the approaches to knowledge acquisition considered up to now are centred on the contents of the patent and tend either to make an interpretation of that content regarding certain domain ontology or to access to the terms defined along with their static definition. These approaches aim at making the patent consulting by domain experts easier.

The approaches we are going to use are not focused on static knowledge, but a selection of evolution-oriented entities in the patent texts is carried out. The works in [1] describe a technological watch system that uses a contextual exploration method for extracting the expressions corresponding to certain notions that the author considers as pertinent, such as change, use or improvement. This method is not based in any knowledge model.

The authors of [2], inspired by TRIZ [3], present the works that are the closest to ours according to their goals and to their use of linguistic engineering tools. Anyway, their approach is different from ours. On the one hand, it is not based on a formal ontology defining the useful concepts; and, on the other hand, it is focused on the tracking of links (called "functions") among the artefact components. This result is a representation of the patent as triplets <element, function, element>, selected from the list of all the triplets <subject, verb, complement> in the text. This representation, though consistent, does not generally satisfy the experts. The retrieval of contradictions is barely tackled in Cascini's works. The contradiction notion is not formally defined; it does not involve other concepts, such as parameter or value.

Other works [4], close to Cascini's ones, are also based on triplets <subject, verb, object> but their goals is to estimate the invention level of a patent.

Our approach is different; it is based on an ontology that is going to be described in Sect. 2.

The technique we are using is a classical technique in information retrieval in texts. It consists in the study of the different ways to express every concept in the ontology and in the development of extraction tools, based on the pattern search in texts.

These patterns are called morpho-syntactic patterns, as they lay on markers that are found in the text, composed of words or sequences of words with a certain prefix or suffix (that is the reason of the "morpho" appellation).

Our ontology is specific to our approach. It is not led by the definition of functions, but by the collection of triplets <element, parameter, value>.

Besides, for the study of patents, we rest on the part of TRIZ that theorize the evolution of artefacts: an inventive patent solves a contradiction that is at the source of the problem. The patent constitutes a partial solution to the problem, because the product evolves in time and afterwards, other contradictions appear. This is the reason why our ontology includes the *problem* and *partial solution* concepts [5]. The goal of this chapter is not to disclose a "good" contradiction, but to identify the contradiction that is solved by a certain inventive patent.

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The ontology has already been used to develop a software tool for the creation of the model and the solution of complex inventive problem, called TRIZAcquisition, fed by data mainly in the form of triplets <element, parameter, value>, thanks to knowledge acquisition from experts.

Therefore, the main goal of our development is to permit "upstream" prospection in patent texts regarding the considered artefact, to find data usable by TRIZAcquisition.

Section 2 presents our approach while Sect. 3 describes the ontology we have developed and that is at the base of these works.

Section 4 describes the methodology we use for extracting contradictions while Sect. 5, finally, presents our conclusions and perspectives of future work.

2 Our Approach

We have constituted an initial corpus, representative of the patents language, consisting of 100 electronic patent files that were published between 2000 and 2009 and that may be downloaded from the Web (http://www.patents.com and http://www.googlepatents.com). These patents belong to different domains. We have collected them by the execution of queries with generic keywords, not linked to a particular domain. The goal of this initial corpus is to collect generic expressions, common to the patents language. The main difficulty is that, even if the patents are in a digital form, they are the result of scanning of printed documents. This fact means that there is a huge work of manual pre-processing for making them exploitable.

The main difficulties encountered when accessing to information in patents come from the specificity of these documents. These relatively short documents are generally structured in paragraphs with standard section titles. They are characterized by long sentences with several repetitions and enumerations in a very particular jargon, which is neither close to the general language nor to the scientific language.

Another source of difficulties comes from the fact that the goal of depositing a patent is more a juridical issue (protection of the intellectual property) than an explanatory one (explanations are sometimes voluntarily confusing). For all these reasons, general tools developed for the processing of documents in general language are not appropriated for their use with patents.

Regarding the goal we have here, another problem we have encountered is about the fact that the abstract model provided by Inventive Design does not generally correspond to the discursive logics that is usually followed in the patents. This abstract model refers; in fact, to the mental model the Inventive Design experts follow while performing a study.

Our approach includes a pre-processing task (performing the analysis of close patents in the same field for chunking essential noun phrases by the use of the *tf-idf* measure) and four steps, which are described in Fig. 1:

1. The extraction of interesting paragraphs, where we can find the disadvantages of the artefact and the improvements proposed by the patent,
2. The tracking of the noun phrases to retain, by comparing the paragraphs retained in phase 1 to the candidate elements (result of the *td-idf* analysis on the initial generic corpus),
3. The use of a linguistic module, permitting the creation of links among elements, parameters and values,
4. The search for antonyms with Wordnet to track the opposite values to the ones found in step 3.

3 The Ontology

The Inventive Design ontology we have developed is generic [6]. It allows the selection of the artefact elements that might be involved in a possible evolution, even if these elements are laid out in a complex way. The aimed result is, then, the population of this generic ontology in a given domain, for the building of a domain model. This model is very different from the usual static domain ontologies, as it only includes information about the evolution of parameters and the consequences of those evolutions.

Our approach tries to follow the same steps as an Inventive Design expert, when he (she) analyses the initial phase and identifies the parameters that will be useful for the definition of the *problem.* The expert has to know which the problem at the origin of the patent is and which *partial solution* is proposed.

The underlying logical structure of the patent texts helps, then, to express information, such as "Considering this artefact this fault has appeared, this patent brings an improvement that removes the problem". The concepts of our ontology, which we will describe below, will permit to consider this logic.

More precisely, a problem expresses the unsatisfying characteristics of a system: it is generally described by expressions of negative opinion. A patent proposes a partial solution, which is expressed by an expression of progress or of improvement. Elements are the components of the system. The elements we are interested in are those whose parameters values change during the improvement brought by the patent. There are two types of parameters: action parameters (where the designer can act on) and evaluation parameters (useful for observing the value changes).

Figure 2 shows an extract of our ontology [6]. Main concepts include elements, parameters, value, contradictions,

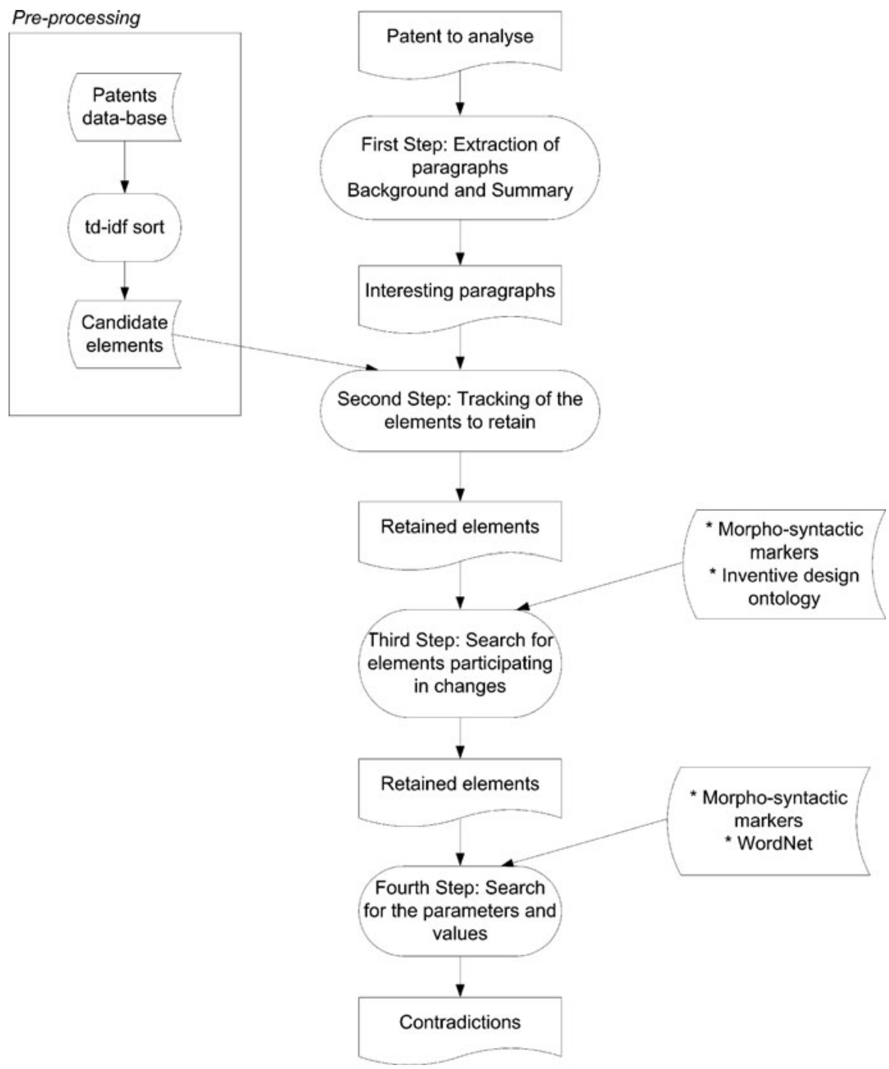

Fig. 1 General view of our approach

problems, partial solutions, and in particular, every notion useful for our goals.

According to these elements to track, our approach involves two steps:

(1) finding the problem whose solution is proposed by the patent,
(2) finding the (partial) solution or improvement brought by the invention.

With this goal in mind, it was needed to understand the way in which these pieces of information are found in the texts, that is, finding the regularities among the informational structure and the morpho-syntactic structure of the text. Afterwards, we have conceived a static retrieval method combined with a rule based module, based on a linguistic analysis.

The contradiction[1] that is solved by the patented product is formulated as an improvement regarding a previous state. In this way, we have to look for the paragraphs in the text that contain a reference to the temporal development of a change, preferably completed by one or several values, qualitative evaluation expressions (negative on the characteristics that constituted the problem, positive on the parameters after the improvement). The opposition between the properties of other systems and the ones of the new system may lead to the discovering of contradictions. The identification of the paragraphs likely to contain opposite values will permit the filtering of the texts and, in this way, the reduction of the search space where more targeted extraction methods will be applied.

[1] As stated in the Introduction, an inventive patent solves a contradiction that is at the source of the problem.

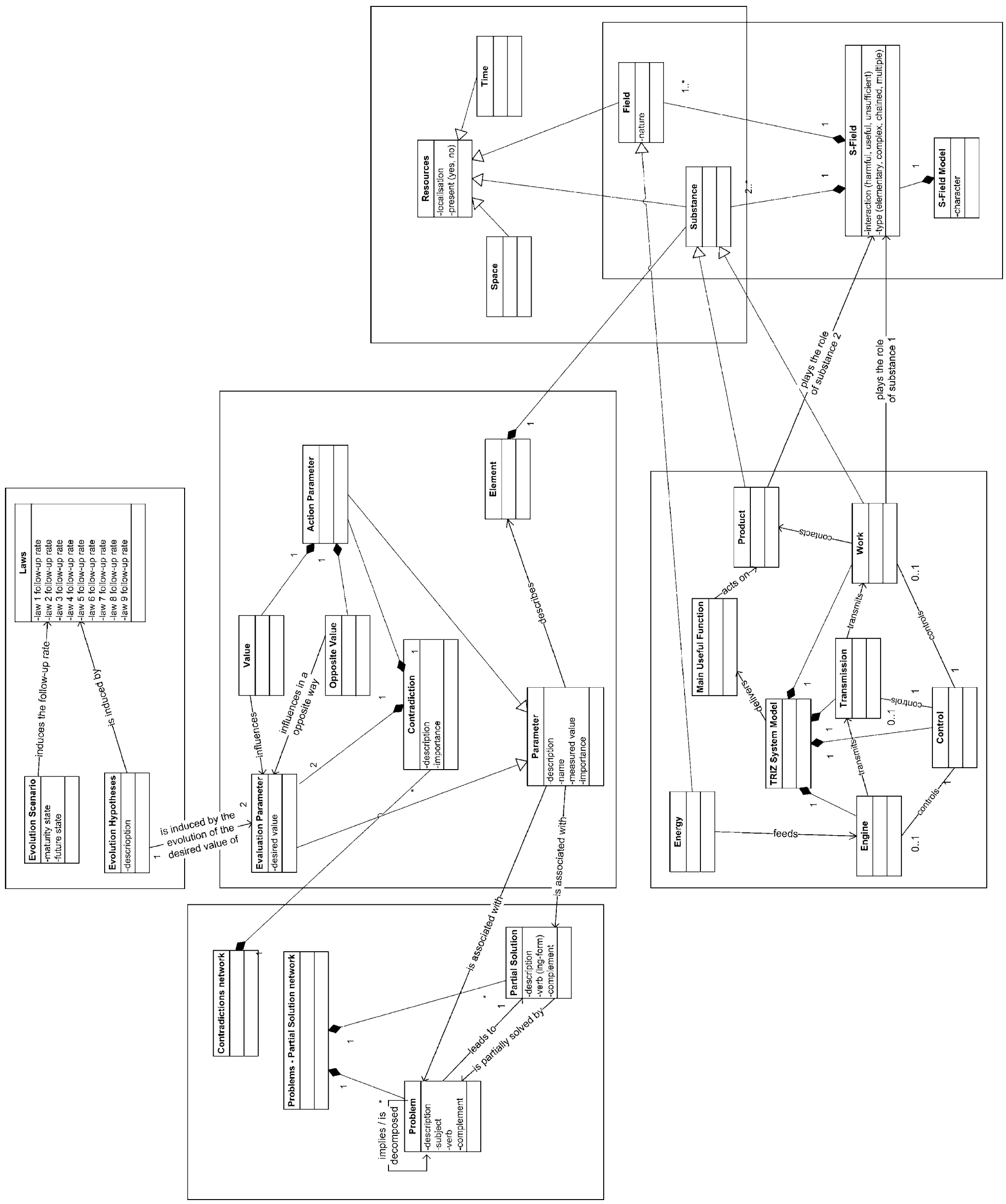

Fig. 2 Reduced view of our ontology

The study of this kind of texts has shown that several comparisons are explicit in the Background or Summary of the Invention sections. Generally, several paragraphs describing the disadvantages of other systems can be found. The expressions that are used here are later used when the invention is described.

The relevant paragraphs are typically organized on the following subjects:

1. The description of the functioning of other systems
2. Difficulties, disadvantages or risks appearing while using other systems
3. Goals of the invention, mainly the ones intended to eliminate the problems mentioned before
4. A partial description of the patented system, explaining the way the problems are solved

3.1 First Step: Checking Interesting Paragraphs Out

The interesting paragraphs are the ones that are going to talk about the state of the art. It is here that the negative aspects of the systems will be found.

Interesting paragraphs also include the ones that are going to talk about advantages; often, there will be an advantage in opposition with a disadvantage of the system; this opposition, as we will see later, might reveal a potential contradiction.

We choose to extract information by using morpho-syntactic markers pointing to pertinent concepts. In this example, we just give a list of some useful ones.

In fact, we have remarked that a restrained number of linguistic structures are used repetitively for describing the state of the art and the improvements to the domain given by the invention. Below there are some examples of those regularities.

State of the art: drawbacks of "typical" systems

***Injection moulding is typically done** in moulds, which operate at high temperatures…*

***Conventionally,** the fluid cover stock material enters the mould cavity…*

***Most injection moulds** comprise halves that mate to define an internal cavity…*

***Typical moulds include means** to heat the moulds at numerous points…*

***However,** the known moulds of this type still **require substantial change over time**…*

*This presents **disadvantages** both in cost and in the downtime required to change over a moulding machine from one part to another…*

***Although** a two level stack mould can produce product at roughly twice the rate possible with a non-stacked mould, mould **costs are considerably higher because of**…*

Summary of the invention: solutions

*A new retractable pin mould for golf balls **has now been discovered which alleviates a number of the problems** of conventional golf ball retractable pin moulds.*

***An object of this invention is to provide improved** quick-changeover cavity inserts…*

***The present invention also provides increased** reliability in the feedback control loop as **it enables the user to eliminate** numerous junctions, which can introduce errors into the control system.*

All the paragraphs that were checked out thanks to the markers above will permit to target the research of the different items involved in the contradictions.

4 Extraction of Contradictions

Regular expressions help identifying the syntactic context and producing the candidate list. The most important thing to do is to detect the oppositions. They can be expressed at a grammatical or lexical level. Certain repetitions are also interesting as far as they may indicate a pertinent text segment.

The key concepts we look for are the elements (the components of the technical system), the parameters of those elements and the corresponding values. In a technical system, among the numerous elements that compose the artefact, we are only interested in those that are going through a change. This change indicates the evolution of the artefact. Parameters have values that may have positive or negative influences. It is often remarked that the three items of the triplet <parameter, value, element> are present together. However, the contradiction is seldom expressed as a whole: the most of the documents only express one value change of a parameter at a time (improving or deterioration). Under these conditions, our system only indicates to the user the contradictions he has to validate. The user also has the possibility of completing the contradiction by hand.

It is necessary now to, on the one hand, identify the three entities; elements, parameters, values; link the parameter to the element, the parameter to the value; and, on the other hand, identify the two possible directions of the variation of the pertinent parameters. These two directions are indicated by oppositions that appear, generally, in different paragraphs.

4.1 Second Step: Tracking of Elements

For identifying the pertinent artefact elements, we look for the domain specific entities and more precisely, the patent specific entities. The words that represent them appear more often in the studied patent that in the rest of the corpus.

Firstly, we proceed to a surface analysis, with the goal of isolating only the nominal groups. In first place, we use a tagger (CRFTagger [7]) that will assign one and only one syntactic category to every word in the text, by statistical criteria. Afterwards, we use a chunker (CRFChunker [8]). This chunker parses the text in elements, among whose we find nominal groups that often correspond to compound nouns. All this is done without performing a fine analysis.

We constitute the lists of candidates, then, by a surface analysis and by eliminating, thanks to certain heuristics [9] and exclusion lists, the compound nouns that cannot be included. We are interested in the relative frequency of the nouns that represent elements in the lemmatized text and we have finally used the measure *tf-idf*, pertinence measure frequently used in data mining and information extraction[2].

$$tf_{i,j} = \frac{n_{i,k}}{\Sigma_k n_{k,j}} \qquad idf_i = \log \frac{|D|}{\|d : t_i \in d\|}$$

$$tf\text{-}idf_{i,j} = tf_{i,j} \times idf_i$$

Where $n_{i,j}$ is the number of occurrences of term i in the document j, and where the denominator is the number of all the occurrences of all the terms in document j, $|D|$ is the total number of documents in the corpus.

During pre-processing, *tf-idf* has been used on a multi-domain initial corpus, with the goal of selecting relevant compound nouns. As it has been explained in Sect. 2, there is a huge amount of manual pre-processing for making the initial corpus automatically exploitable. This is the reason why, unfortunately, we have not been able, yet, to compare the relevance of *tf-idf* while changing the size of the initial corpus. Experiments are being carried out.

During this step, *tf-idf* is used on the patent we are analysing to select the nouns that are the most characteristic of it.

This measure permits to select around ten candidate elements by document with the configuration we have chosen (a minimal value that is significantly lower for the nouns that for the other grammatical categories). We have searched for the words with a high *tf-idf* value and acting as headers of nominal groups, as well as the attribute adjectives. Elements are tracked with a good recall, but the density of their occurrences demand even more filtering.

In addition, we plan to compile the corpus in a different way, by choosing first a set of texts belonging to the domain of the artefact. The value *tf-idf* will bring then more specific elements to the document and less usual elements in the domain. However, we will have to check if this better selection does not introduce any silence in the filling up of our model.

4.2 Third Step: Use of the Linguistic Module

The elements identified by the static filtering have to be filtered again on linguistic criteria. The linguistic module that is integrated in the system is implemented as a set of transducers; it permits to create the links among elements, parameters and values and to provide the annotations that correspond to the roles they play according to Inventive Design.

After the linguistic analysis of the corpus, we have collected the markers that might be candidates; afterwards we have selected the more efficient ones. We have used NOOJ [10] for considering them during the annotation and the extraction. NOOJ is a tool that allows the use of morpho-syntactic patterns given as graphical objects, facilitating the readability and the manipulation of these patterns.

We have retained 60 verbs, 137 adverbs, 473 adjectives and 273 nouns. We noted that the verbs that are used in patents texts are mostly action verbs, and more precisely, change verbs or verbs that indicate a state change. This kind of verbs are the most productive regarding the detection of parameters and values. Frequent modal verbs in these texts generally express different degrees of "possibility" (need or certitude). When, in the corpus, these modal verbs are accompanied by the auxiliary "be" and the whole phrase is followed by certain grammatical indexes, they permit the localisation of certain searched pieces of information.

Adjectives often carry values themselves. We have also remarked the frequent use of oppositions between adjectives in the corpus.

Adverbs are generally a category difficult to study, because the meaning of the sentence depends on their scope. However, choosing the adverbs that are interesting for our goals has been easy, because we are only interested in evaluation adverbs.

Authors of patents use very complex compound nouns in order to assemble a maximum of information in a sentence, and they use a huge quantity of words to describe the artefact and its components. From this fact, we only retain the nouns that correspond to parameters or to values.

We have implemented the annotation grammars in NOOJ. These grammars correspond to enriched transducers (use of variables and constraints, queries of dictionaries while performing the analysis).

We have constituted two specific dictionaries and edited 46 graphs on the base of the analysis results. These graphs

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[2] tf-idf (*term frequency – inverse document frequency*) is a weighting method that permits to quantify the informational importance of a word in a set of documents. A word appearing everywhere does not bring any information, a word that appears in a subset of the documents permits the characterization of this subset.

define the constraints to take into account while doing the annotation. For example, oppositions have to appear in the same sentence, verbs have to be accompanied by certain indexes to be annotated; the annotation is effectively performed only when at least two researched notions exist, and so on.

The application of annotation grammars finally provides, as an output, the annotated text in exportable XML format.

4.3 Fourth Step: Search for Antonyms

After having identified the elements that participate in changes, it is needed to search for the corresponding parameters and values.

A module that uses Wordnet tries to track the opposite values, knowing that the oppositions are among the descriptions of the invention and in the Prior Art section.

Parameters that change their values may be, on the one hand, at the lexical level, either antonymic adjectives or participles or couple of "negative-positive" verbs. On the other hand, at the syntactic level, they can be complex syntactic markers, indicating which roles are played by the entities in the close context.

Lexical oppositions are easier to identify, it is about couples of antonymic adjectives or participles, which are linked (by reference or by syntax) to the same elements (nominal syntagms). For example:

> However, the plastic materials which can be released by resiliently deforming such an undercut area in the prior art injection blow moulding process are limited to relatively *soft* plastic materials.
> Another object of the present invention is to provide an injection mould, which can release the core mould by resiliently deforming the undercut formed on the lip portion even if it is moulded of a relatively *hard* plastic material.

Except from antonyms, present within the nominal groups having an identical structure, we have also remarked the frequent presence of opposition markers: for example, "limited to" vs. "even if" that permits to express opposed values.

Useful antonyms are the ones that are expressed by adjectives within nominal groups ("hard plastic material") and the ones that appear between the adjectives and participles that have a predicative function as syntactic headers. In addition, there are cases where nouns refer to properties expressing values of parameters. The module calls Wordnet and chooses a subset of the adjective couples that are result of this call. This subset excludes the adjectives that refer to location, order, etc (for example, first-second/last, inner-outer) and that generally precise the elements of the technical system without expressing value evaluations.

Syntactic oppositions are harder to identify. They manifest, often, by lexical repetitions in different contexts; for example, the same action is expressed once in an affirmative context and, later, used again in a negative context:

> However, such a mould structure *disables the release* of a moulding from the mould. Namely, the undercut of the moulded preform as well as the mould *will be damaged* when the injection core mould is drawn out from the interior of the moulded preform.
> It is therefore an object of the present invention to provide an injection mould which can injection mould a preform to be biaxially stretch blow moulded with a lip portion having an undercut and also which *can release the core mould* without damaging of the undercut.

The two couples of syntactic oppositions are:

"disables the release of a moulding" vs. "can release the core mould"
"the undercut will be damaged" vs. "without damaging the undercut"

These structures can be found by regular expressions, coding the morpho-syntactic patterns. However, while the couples (elements, their associated parameters) or (parameters, their associated values) have to be looked for in the same sentence, oppositions have to be searched for in different paragraphs. The research has to take into account the lexical repetitions and examine the grammatical context of the repeated segments for extracting the potentially pertinent oppositions.

5 Conclusion

These preliminary works have permitted the observation of the difficulties associated to the extraction tasks in our approach. A real evaluation of the efficiency of our processing would need the presence of two experts: an expert in inventive design and an expert in the artefact domain; that is the reason why we have, at this moment, only worked within the plastics field. It was a means for us to test our approach.

The approach seems pertinent, but additional confirming work remains to be completed, yet. The markers base is still imperfect and surely incomplete. Recall is today about 60% and precision is about 70%; both measures are improvable. The main difficulty concerns the extraction of contradictions that are expressed in different ways and at different locations in the text, which may be far away from each other. Moreover, the contradiction is seldom complete, that is that the two opposite aspects do not always appear explicitly.

However, it is necessary to place ourselves in the context of the use experts do of patents with the goal of feeding our software. The use of an operational module implementing these sequences of prototype processing tasks will, with no doubts, save a considerable amount of time, even if a certain quantity of outputs will need user validation.

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An ISAL Approach for Design Rationale Discovery Using Patent Documents

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Abstract The management of design rationale (DR) is an important task in design study. However, existing DR approaches are unable to discover DR from the large amount of archived design documents. It motivates us to propose a new DR representation model, ISAL (issue, solution and artifact layer), using patent documents. In this chapter, we first reviewed existing DR approaches. Then, we proposed an ISAL for DR discovery. Finally, we have conceptually evaluated ISAL and IBIS (Issue-based information system) using sample patents of inkjet printer. The results demonstrate the merits of ISAL model proposed.

Keywords Design rationale · Representation model · Patent documents

1 Introduction

In general, DR refers to the explanation of why an artifact is designed the way it is [1, 2]. DR includes all the background information and knowledge such as the issues discussed along the design process, reasons behind a design decision, arguments led to a particular decision and so on. DR is well recognized as critical information and knowledge to engineering designers and organizations for design reuse, design reasoning and design evaluation [3]. For example, designers in Rolls-Royce are encouraged to use DRed, a design rationale editor, to capture design issues, hypotheses, arguments etc. [4]. It is one of key initiatives that aim to achieve an effective management of design knowledge and to protect the company's investment in R&D.

Several studies have focused on DR representation in design knowledge management. One of the challenging issues in DR management generally lies in how to build a DR knowledge base. The existing DR systems mainly center on capturing DR in daily design activities manually, which is time consuming and labor intensive. Moreover, they can not extract DR from design archival documents, such as test reports, patent databases, design forums and customer surveys. DRs presented in these resources have an informal and unstructured shape and have not been reported so far in building DR repository. In addition, open accessible DR data are not available for DR system evaluation and benchmarking. The common evaluation method is case study [5]. With respect to data resources, patent documents are recognized as high quality data which are open and public accessible compared to design documents which are often confidential. Patent documents contain rich information about DR, technology development and so on. In addition, they are more reliable and systematic than other online resources. It motivates us to focus on the study of modeling and evaluating DR representation using patent documents.

In this study, we propose a DR representation model, ISAL (issue, solution and artifact layer), and intend to compare DR models using patent documents. Section 2 presents the previous studies on DR and patent processing. Section 3 details our ISAL model using patent documents. Then a case study of DR representation based on ISAL and IBIS methods (one of the earliest and influential method) are elaborated in Sect. 4. Section 5 concludes.

2 Related Work

2.1 DR Systems

Since the early 1980s, several research studies on DR systems were reported. DR representation is well recognized due to its vital role in DR systems for retrieval and design reuse [2]. Approaches in representing DR can be roughly

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categorized into three main branches. The first branch is argument-based representation, where its original one is Issue-based Information System (IBIS) [6].

IBIS was proposed in order to support coordination and planning of decision process [6]. Using issue-based conceptual elements, it helps to structure issues raised in the deliberation process as well as to provide information pertinent to discourses. Basically, IBIS consists of three types of element, i.e. issues, positions and arguments, and relations which denote the relationships among different elements. Issues represent anything that needs to be discussed, deliberated and integrated into argumentation during a design project. Positions denote the ways or answers of resolving the issues. Arguments describe the statements supporting or objecting the positions. These element types can be connected to each other in order to form an issue network by different relations [7]. Issues, positions and arguments can become "generalized" or "specialized" by the same element type. Any other element type can "question" or "be suggested by" an issue. For instance, an issue can be proposed to question the position suggested by other designers [8].

Some graphical DR systems were implemented based on IBIS, such as DR editor (DRed) [4] and Compendium tool [9]. In addition, several other approaches were derived from IBIS due to its simple but powerful concepts of IBIS, such as the Procedural Hierarchy of Issues (PHI) [10], DR retrieval framework [11] and Kuaba approach [12]. Another argument-based model is Question, Option and Criteria. It focuses on providing a structure representation of design alternatives [13]. Software Engineering Using Design RATionale (SEURAT) is another DR system, which extends the DR language (DRL) by using an argument ontology [14]. Although these systems were implemented and used in several projects, they have not been widely spread in the industrial engineering [5].

Besides IBIS, another approach is functional representations which center on describing how the device works (or intended to work) [15] and how artifacts serve or satisfy an pre-specified functionality, e.g. causal components of DR and their functions [16]. Finally, in literature, it has also reported a rationale-based architecture model for software architecture design [17, 18].

However, several questions remain unsolved in the existing DR representation models. Firstly, they cannot help to discover DR from unstructured documents, such as archived design documents and patents. Secondly, the extended versions of classic DR models have made the new DR models even more complex. Thirdly, in the existing DR approaches, the information about how the design components are related to each other remains implicit. Therefore, such models possess limited features to support modeling, retrieving and managing the rich information related to DR.

2.2 Text Mining for Patent Processing

As the ever increasing number of patent documents, text mining techniques have been widely introduced and applied in patent processing such as patent classification, patent information extraction and patent summarization to discover information and facilitate patent management.

Patent classification attempts to alleviate human efforts in assigning patents into their corresponding class using text mining approaches. Kim and Choi [19] proposed a patent document categorization method based on patent semantic structural information like claim, purpose and application field using k-nearest neighbor approach. Lai and Wu [20] attempted to build up a patent classification system for a specific industry using co-citation analysis of bibliometrics. In order to facilitate TRIZ users, He and Loh [21] aimed to assign patent documents according to Inventive Principles. In addition, text mining techniques also have been applied for patent summarization. For example, Trappey et al. [22] developed a patent summary generation approach by integrating the concepts of key phrase recognition and other significant information like title phrase and relevant phrase. Moreover, Kang et al. [23] investigated cluster-based retrieval for the task of invalidity search of patents. Tseng et al. [24] presented several text mining techniques including summary extraction, feature selection, term association and clustering for patent analysis, such as topic identification, topic mapping and patent summarization.

2.3 Patent Processing for Design Assistance

Since patent documents contain rich technology, rich research efforts have been devoted to patent processing for engineering design like R&D planning, innovation and concept generation. In order to help designers to better understand the technology, Choi and Park attempted to monitor the organic structure of technology by developing patent document paths from a patent citation network. Soo et al. [25] intended to develop a cooperative multi-agent platform to integrate patent document analysis with inventive problem solving method TRIZ. The platform was built by extracting structure information from patents with the aid of ontology and natural language processing. Suh and Park [26] aimed to provide a service-oriented technology roadmap for R&D strategy of service industry using patent map. This map was a 3D visualization method and analysis tool based on keywords extracting by clustering approaches. Shih et al. [27] proposed a patent trend change mining approaches by combining association rule change mining with patent indicators to identify changes in patent trends to analyze the R&D activities of competitors. Kim et al. [28] intend to recognize the progresses of technologies for R&D by forming a semantic patent network based on the extracted keywords and clustering techniques. Lee et al. [29] utilized keyword-based patent map to discover new technology opportunities to support new technology creation activities using text mining and principle component analysis. In summary, the applications of patent processing in engineering design are means for designers to further obtain and understand design knowledge and information.

3 Design Rational Representation Model Using Patent Documents

3.1 ISAL Model

In this section, we propose an ISAL model for DR using patent documents. The ISAL modeling consists of two stages. The first stage is to model DR in a single patent document. The second stage focuses on forming a DR network for multiple patent documents [30].

In the first stage, by analyzing the content of DR and also the structure of patent documents, an ISAL model is proposed to represent DR in a singe patent document, i.e. issue layer, design solution layer and artifact layer shown in Fig. 1.

- Issue layer describes the motivation. It includes shortcomings, limitations, or challenges related to the previous patents or designs as well as the demands or needs. Here, we assume that each patent document focuses on one single issue although the concept of an issue can be defined in different ways by designers, e.g. some issues can be further divided into sub issues. The issue concerned can be discovered from specific sections in each patent document, i.e. the description of related arts and the invention background.
- Design solution layer describes how the issues can be solved and how the artifact can be created. It links up the issue layer and the artifact layer. Design solution layer consists of design solution points. Design solution points refer to the processes or methods that are designed to address the issue. It can be represented as the causality relation between components, such as solutions and their corresponding effects. This type of information can be found in the brief summary of an invention and its detailed description as well.
- Artifact layer explains design components, their features and properties as well as the component relations. The component interaction and component's properties reveal the artifact's mechanism rationale. The related information can be obtained from sections of claims and detailed description of the invention.

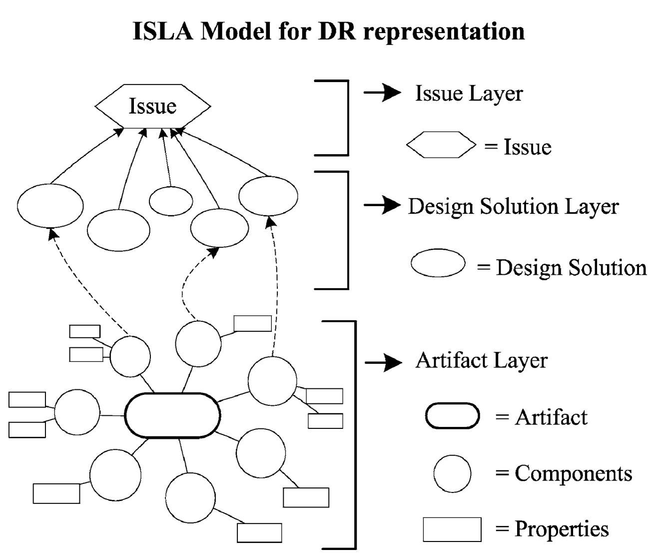

Fig. 1 ISAL model for DR representation

In our previous work, we have researched concept extraction and clustering [31, 32], term weighting [33], text summarization [34, 35] and text classification [33, 36, 37]. Therefore, for the issue layer, we are exploring a concept-based summarization method to extract concept-bearing sentences to represent the issue. In order to discover design solution points, we are working on generating solution-effect pairs using association rules and causality analysis. For the artifact layer, we are proposing a concept map approach to represent components and their relations.

In Fig. 1, the arrow between issue, design solution and component represents "support" relation. An issue is the design motivation. In order to deal with the issue, design solution points are introduced to stress the improvement methods or any significant ideas of the invention. Correspondingly, the artifact layer demonstrates components, their features and relations that are all associated with the design solution points. Design solution points link up the issue and artifact components.

The second stage intends to model DR representation for multiple patent documents by discovering the implicit relations between DRs to form a DR network, which in turn helps to understand design related information from a holistic and comprehensive perspective. For the issue layer, the relations of issues discussed in different patent documents are discovered using citation and similarity metrics. Similarity metric is applied to assess the content comparability between issues. For the design solution layer, we group the design solution points as a cluster if they relate to the same components. Since solution-effect relations between the two components can be described from different aspects in different patens, the clustered cause-effect information is able to give a comprehensive view on component interactions. For the artifact layer, the same components can be merged to form an artifact component map. Since the properties or features of the same component described in patents can be different, the merge operation facilitates the understanding of artifact characteristics.

3.2 Overview of the Proposed DR Retrieval System

Figure 2 shows the proposed DR retrieval system framework using patent documents based on our ISAL model. The process of building DR repository starts with collecting patent documents from patent database, e.g. United States Patent and Trademark Office (USPTO). Then, each patent is processed for DR discovery according to the ISAL model. Next, the relation analysis among multiple DRs is triggered to form a DR network by the citation and similarity between DRs.

After the DR repository is developed, it serves as the knowledge base for DR search and retrieval. Unlike the typical information retrieval system using keywords based search, our DR representation model can help to support rationale-related search and retrieval which is able to provide information from three layers of details. For example, if the issue of ink jet printer "reducing crosstalk" is queried, relevant design methods in design solution layer will be retrieved and clustered. Meanwhile, a structural view of components involved in the mechanism can be provided by design components linked to the relevant design solutions. In the similar way, designers may raise a query "ink jet printer" in artifact layer in order to get an overview of efforts that emphasizes this artifact or component or in order to have an idea of its technological trend. From issue layer, it is able to cluster and sort out the relevant DRs. In terms of how similar the issues or questions are, difference in artifact structure can also be identified because each issue is associated with their corresponding artifact layer. If we exam from the artifact angle, it is possible to assign the retrieved DRs into several clusters based on the artifact components. In this way, we can link the issue back to their corresponding artifacts. Furthermore, it becomes apparent to see which part of the artifact is actually receiving more attention because this is the issue being frequently addressed.

4 Case Study: Design Rationale Representation Model Comparison

Several DR approaches have been reported to represent DR for DR management and retrieval. However, the comparison among DR models is a difficult and challenging task.

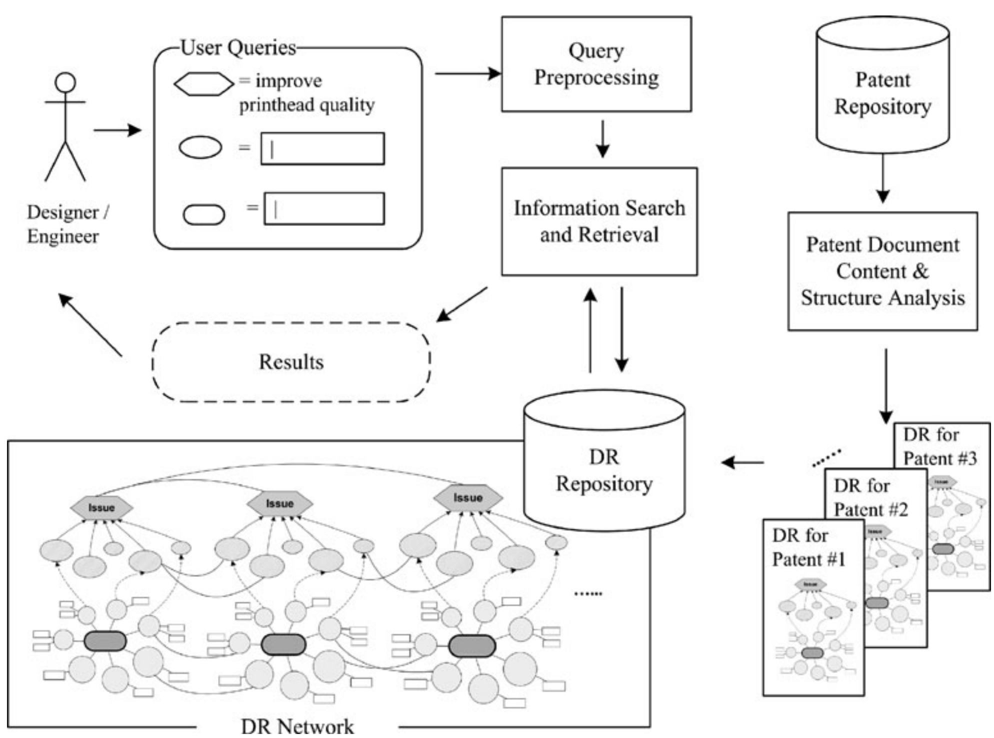

Fig. 2 The overview of DR retrieval model using patent documents

Burge et al. have investigated 56 approaches [5]. Their results show that nearly half of the approaches have no evaluation description and the rest often use case study for conceptual evaluation. Moreover, cases used in the literature are different and not open for test purpose. It is largely because design knowledge is confidential and the test data for DR study and benchmarking are not publicly accessible.

Here, we promote using patent documents as test data. In our case study, we compare ISAL with IBIS using the same patents. IBIS is selected because it is regarded as the origin of most DR representation approaches and it is the point of reference for most of the research in this field [7]. For test purpose, we choose two patent documents all related to ink-jet printer. P1 (Patent No. 5278584) focuses on dealing with some disadvantages of the prior art ink feed design. In P1 (Patent No. 6746107), the inventors aim to increase the nozzle packing densities. In Sect. 4.1, Examples of DR representation using ISAL are given. Then in Sect. 4.2, we try to interpret DR based on IBIS. Lastly, the comparison results are analyzed from motivation, structure and operation aspects of different models. Although such an evaluation could not fully study the performance of these DR models, we intend to conceptually validate ISAL and give an idea of how different ISAL and IBIS are.

4.1 DR Representation Using ISAL

Each individual column in Fig. 3 shows a portion of DR discovered in a single patent document based on ISAL model with their patent number on the top.

In the issue layer, issue presented in the patent is actually summarized from "Background of the invention" section, including the concepts described from the negative points of view, such as "fragile" (Seg_2 in P1), and the concepts represented the direct intentions, such as "...is a desire". For example, the issue in P2 consists of three segments (Seg_1-3). They indicate the motivation why this invention is created and designed. Both Seg_1 and Seg_2 refer to the needs for higher nozzle packing densities. Meanwhile, Seg_3 mentions the crosstalk problem that should be concerned when designing the high density nozzle. In a quick summary, the issue layer presents the motivation why this invention artifact is initiated.

Compared with issue layer, design solution layer introduces more details related to methods or mechanisms when dealing with the relevant issues. The design solutions are discovered from the "Detailed description" section, like the phrase pairs or sentence pairs bearing a strong solution-effect relation. For example, in the design solution layer of P2, the pair of So_1 and Ef_1 suggests that by arranging "each column containing 304 nozzles...per printhead", the corresponding result can be obtained, such as "these embodiments of printhead can...print a greater resolution...". In addition, from the design solution layer, it helps to discover the relations between relevant solution-effect pairs. As shown in P1, by applying the method mentioned in So_1, "the edge feed feature", it leads to the effect that the substrate can be made smaller (Ef_1). Meanwhile, referring to So_2, "making the substrate smaller", it further results in lowering the material cost per substrate and making less fragile in the substrate. Through the Ef-So connection between solution-effect pairs, it helps to unveil part of the reasons why the production time and the substrate fragility issue (Seg_1 and Seg_2) can be solved. Note the solid line represents that the design solution points are associated with the said issue. Overall, design solutions respond to the said issue by representing possible methods.

The artifact structure is shown in the artifact layer. Design components and their relations are mined from the sections like "Claims" and "Detailed description". These sections represent component, their properties and relations. Figure 3 visualizes the invention structure. White boxes represent artifact components and rounded rectangle boxes represent those features associated with the components. The edges attached with words or phrases represent semantic relations between two components or features. For example, from the artifact layer in P1, "printhead" is comprised of several parts, such as "substrate", "fluid channel" and "nozzle member". When focusing on "fluid channel", "vaporization chambers" communicate with "ink orifice" and "heating means". Carefully look at the feature "substrate", more embodiment details can be obtained, such as "having a top surface..." and "having a first outer edge...". Besides, dash lines are specified if components or their features are associated with design solution points in the design solution layer. This indicates that different components support such methods. For instance, "substrate" and its feature "edges" are related to So_1 and So_2. This indicates that "substrate" is one of the important components in solving the related issue. By referring to the links between design solution layer and artifact layer, various key components and their interactions can thus be easily understood.

In order to further reveal relations between relevant DRs, we use patent sectional information and DR information for the inner DR relationship analysis. By measuring the similarities among issue, design solution and artifact layers respectively, the results indicate that P1 and P2 are related to each other in some aspects. According to the issue layer, Seg_3 of P1 and Seg_3 of P2 suggest that both P1 and P2 partially focus on dealing with the crosstalk problem. In addition, the design component structure in the artifact layer shows the close relationship between P1 and P2.

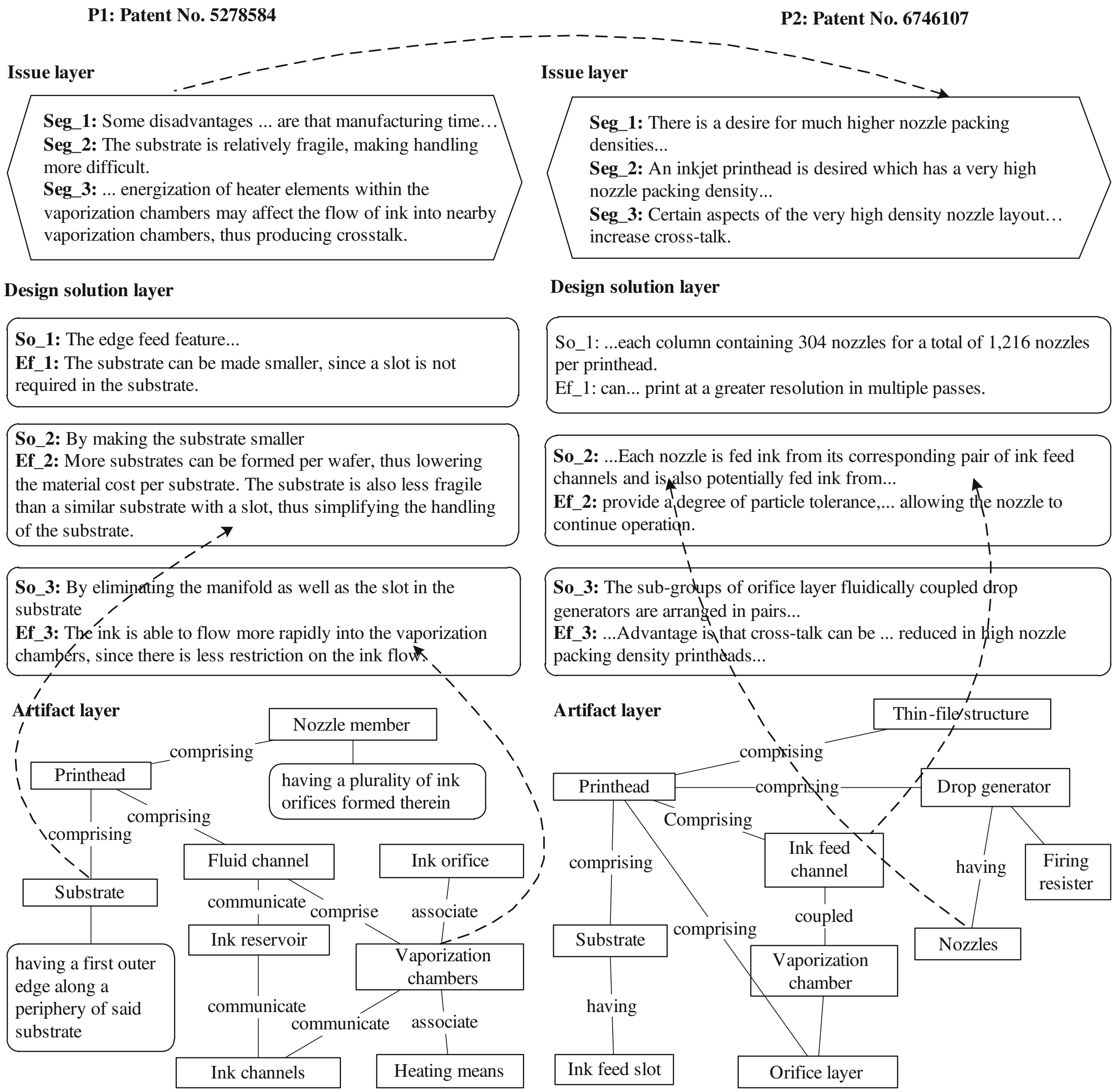

Fig. 3 DR representation using ISAL

As shown in P1, "substrate", "ink channels", "ink orifice" and "vaporization chambers" are some of the key components since they are related to some solutions. In P2, some important components are "ink feed channel", "vaporization chambers" and "orifice layer". From the similar components, the relevant solutions can be integrated to further understand how to tackle with the crosstalk problem. As shown in design solution layer, "eliminating the manifold as well as the slot in the substrate" (So_3 in P1) and "arranging the sub-group of orifice layer in pairs" (So_3 in P2) are two pieces of approach in addressing the crosstalk problem. The components mentioned in the said solutions are suggested as the important factors when designing the printhead. By integrating DRs of multiple patent documents to form the DR network, more details can be obtained for analyzing particular components.

4.2 DR Representation Based on IBIS

Figure 4 partially shows the DR of both P1 (Patent No. 5278584) and P2 (Patent No. 6746107) based on the concepts of IBIS. Using IBIS model, issue drives the DR network with the details of positions and arguments. For example, in P1, starting with the issue “what does a printhead comprise in the prior art design”, one position which responds to the said issue is the answer which describes the components like “ink channels. . .orifice plate or nozzle member and silicon substrate”. This is regarded as a general question in printhead design. To further differentiate this invention from relevant patents, some challenges or problematic issues are questioned, such as what are “some disadvantages of this type of prior art ink feed design”. To tackle this nontrivial question, it is specified by three issues, i.e. the manufacturing time problem, fragile problem and the crosstalk problem. With respect to the manufacturing problem, the position of “the edge feed feature, where ink flows around the sides of the substrate. . .” is elicited as a piece of approach. Moreover, by interpreting P1, two pieces of arguments are pointed out to support and evaluate this said position, such as “more substrates can be formed per wafer, thus lowering the material cost per substrate.” and “the substrate can be made smaller, since a slot is not required in the substrate”. This issue-position-argument chain implies part of the reasons why the edge feed features is designed the way it is.

IBIS is an argumentation-based DR representation, which models the design space as a network of issues discussed along the design course [8]. In this IBIS network, the issue node type plays a vital role in linking DR in a structural manner, which facilitates designers to deliberate issues from both broad and deep perspectives. For instance in P2, on the

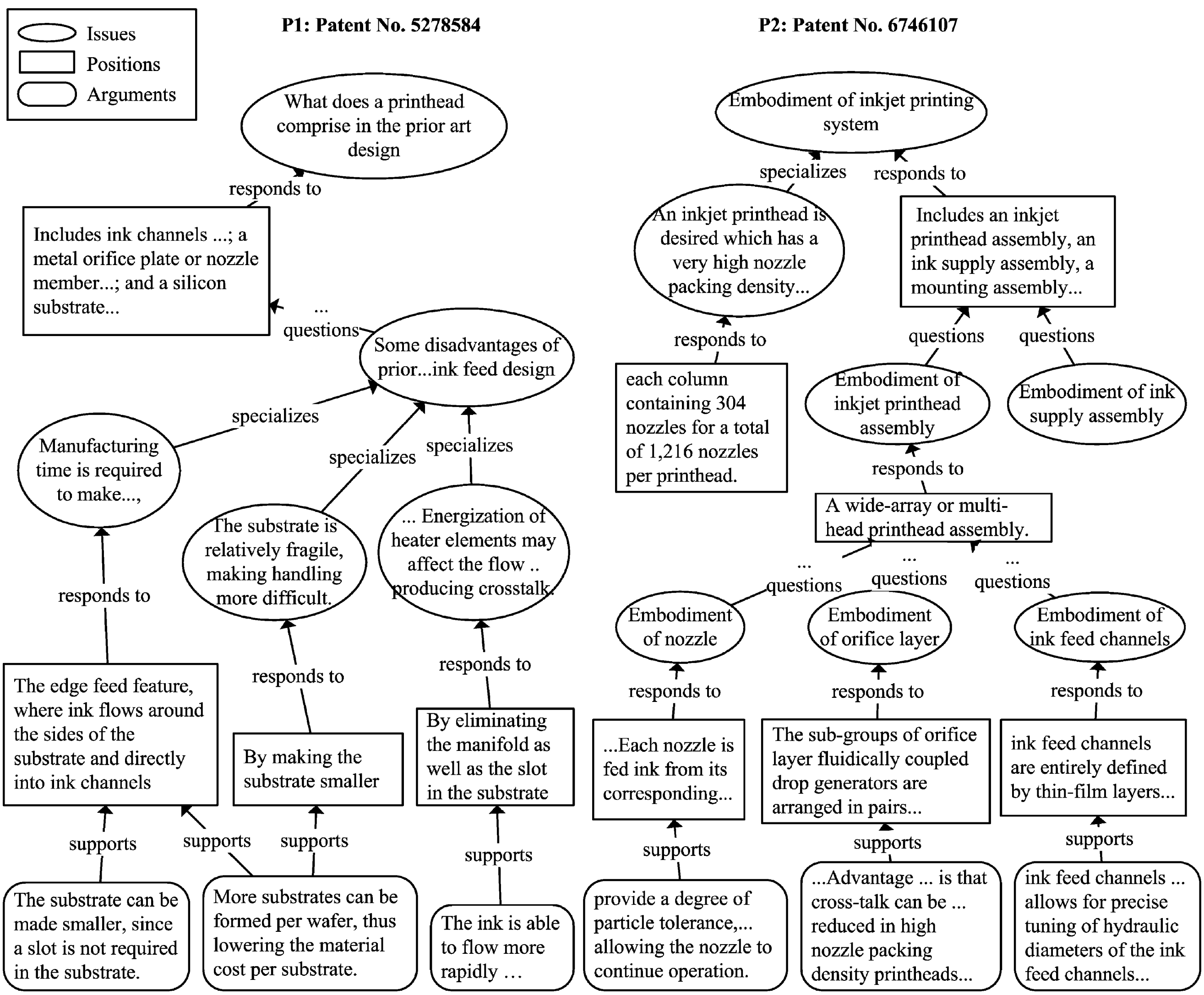

Fig. 4 DR representation using IBIS method

Table 1 Comparison results between ISAL and IBIS

		ISAL	IBIS
Motivation	DR resources	Archival documents, especially patents	Mainly focus on DR in design processes
	DR Capture manner	Use text mining techniques	Manually
	Data scale	Can handle large scale of patents	Small scale
Representation approach	Motivational reasons	Both represent issues, questions or topics which motivate the inventions.	
	Design solutions	Both describe methods and arguments	
	Artifact information	Can visualize the artifact structure	Very implicit
Operation supported	Multiple information	Retrieval results can be interpreted from three layers perspectives.	N/A
	Query	Complex query using NLP techniques	Keywords search (such as Compendium)

one hand the initial issue about the "embodiment of inkjet printing system" is specialized by a question related to the requirement of "a printhead. . .has a very high nozzle packing density". This question is further narrowed down to the niche occupied by P2. On the other hand, this issue is responded by a position which suggests that an inkjet printing system should include "an inkjet printhead assembly, an ink supply assembly and a mounting assembly. . ." Then two issues are raised, i.e. the embodiment of printhead assembly and ink supply assembly. A further investigation shows that three issues, namely the "embodiment of nozzle", "embodiment of orifice layer" and "embodiment of ink feed channels", actually question the arguments related to the composition of printhead die. These issues help the designers to think deeply and broadly when investigating the relevant components.

4.3 Comparison Between ISAL and IBIS

In this section, to better understand the differences between ISAL and IBIS approach, we conduct a conceptual comparison from three main perspectives, i.e. motivation, representation and operation wise (as shown in Table 1).

- Motivations, which explain why a DR model is proposed, are the essential factors that distinguish these two models. IBIS method focuses on capturing and recording DR along the design process in order to facilitate a discussion amongst the stakeholders. Since 1980s, several IBIS variants have been developed to graphically support DR capture. However, they only depend on human efforts to document DR in a formal or semi-formal structure. Different from IBIS, ISAL stresses mining DR from the archived design documents. In other words, our proposed method aims to develop a computational model which can extract DR from unstructured design texts and cast it into a structured template. Although both IBIS and ISAL are methods help to interpret unstructured DR into a formal or semiformal manner, major difference exists. As shown Figs. 3 and 4, if we look carefully from the issue perspective, DR represented based on IBIS seems to be more human readable then using ISAL. However, DR representation using IBIS will lead to different results if multiple designers are involved in the process, since the concept of an issue can be defined in many ways by designers. Therefore, it indicates that IBIS has the problem in controlling the issue granularity among different patents, while this is not a question for ISAL. Furthermore, ISAL can handle large scale of documents, since it is proposed to automatically extract DR from the large amount of design documents, while IBIS method requires extensive human involvements. It is therefore highly desirable if we can discover DR from archived texts by counting on ISAL.
- As for the representation, IBIS and ISAL both share some overlaps, but also possess different features. From the perspective of elements, IBIS and ISAL share similar concepts like issues, positions and design solutions. For example, IBIS method has an issue element type and ISAL uses issue layer to represent problems and intentions. In addition, in order to represent the way or method to resolve an issue, IBIS uses Positions and Arguments while ISAL introduces solution-effect pair. This indicates that both IBIS and ISAL emphasize motivational reasons, design methods or ways and arguments which are critically concerned in DR. However, the major difference is that ISAL stresses artifact information represented in the artifact layer, since DR is concerned in a particular artifact design. The artifact structure can help to understand DR in a holistic view. Unfortunately, the information about how the design components are related to each other remains implicit in IBIS. From the linkage perspective, IBIS differs from our proposed model. In IBIS, the relationships between nodes are predefined and assigned manually. This process requires human effort. In ISAL, the linkages between layers represent "relevant" or "support" relations. In addition, connections among different

DRs in multiple patent documents are explored based on similarity among respective layers. This computational process can help to discover the relations among multiple documents.

- With respect to the operations, IBIS method, such as DR system Compendium [25], can only process keyword search by exactly matching the words that appear in the contents. As mentioned in Sect. 3.2, ISAL is exploring to handle more complex queries, such as cross-query from multiple layers. In addition, since DR are represented from issue, design solution and artifact perspectives, ISAL approach can help to interpret the retrieval DR from these three aspects.

Overall, the comparison states several merits of our ISAL model compared with IBIS method. Using the text mining techniques, the ISAL can handle large scale of patent documents. Meanwhile, it is evident that the artifact layer in ISAL further helps to give a more explicit explanation of design components than which IBIS can support. Moreover, ISAL can support more comprehensive retrieval interaction, such as multifaceted query from different layers.

5 Conclusions and Future Work

In this chapter, we propose an ISAL, i.e. issue, solution and artifact layer model, to extract and manage DR from the archived design documents, like patent documents which obviously contain quality information of DR and are also open to public. Using a case study of inkjet printerhead, we conceptually evaluate ISAL and IBIS in representing DR based on the identical sample patents. The results show that compared with IBIS, ISAL possesses the ability to explain the rationale of artifact structure design and it is able to support DR retrieval from multiple aspects, such as issue, design solution and artifact perspectives. Currently, we are focusing on fully implementing the ISAL model. We are working on exploring a concept-based approach for issues identification, generation solution-effect pairs using association rule for solution layer and proposing concept mapping approach for artifact information extraction. We intend to extract the patterns in representing rationale information while other linguistic challenges in patent processing [38], such as synonyms, polysemy, i.e. one word having multiple meanings, and single conceptual entries repressed by multi-word terms, are not the major concerns in our study. Meanwhile, we are manually preparing a large dataset with 300 HP patents tagged to further test the performance of DR discovery approaches and their scalability. Moreover, these patents are manually built based on IBIS for real rationale case study between IBIS and our ISAL.

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Automatically Characterizing Products through Product Aspects

P.-A. Verhaegen, J. D'hondt, D. Vandevenne, S. Dewulf, and J.R. Duflou

Abstract Like most front-end design and problem solving methodologies, TRIZ requires users to abstract their specific system or problem, analyze it through the methodology, and, if applicable, map it back to a specific situation. A methodology and algorithm are proposed that can eliminate this subjective and arduous mapping by formalizing automatically identified, fine-grained product dimensions or Product Aspects. These Product Aspects allow for automatic product characterization, which is a key technology to enable different automated functionalities in idea generation and problem solving contexts, such as automated trend analysis and searching for similar products.

Keywords Design methodology · TRIZ · Patent mining · Product aspect · Properties

1 Introduction

The Theory of Inventive Problem Solving (TRIZ) is based on manual analysis of what TRIZ practitioners estimate to be around 40,000 innovative patents. By deductive reasoning, the applied specific innovative solutions were mapped to a small number of extracted abstract inventive principles. This specific to abstract mapping was the basis for a methodology and a set of tools for generating innovative solutions. The most popular TRIZ tools are [1]:

- the Contradiction Matrix to solve Technical Contradictions;
- the Separations Principles to solve Physical Contradictions;
- Substance-Field (SU-Field) modeling and the Inventive Standards to transform technical systems;
- ARIZ as a list of logical procedures for eliminating contradictions; and
- TRIZ Trends as a system of laws that govern engineering system evolution.

Before using any of these tools, TRIZ users rely on their experience and skills to map a specific problem to a more abstracted problem formulation. After applying the tools, TRIZ users map the obtained abstract solutions back to their specific situation. The black arrows in Fig. 1 illustrate this approach. TRIZ shares this need for a higher level of abstraction with most other problem solving, front-end design and creativity techniques, such as bio-inspired design and design-by-analogy. In this respect, TRIZ can be regarded as a schematized cognitive framework evolved from the analysis of patents by problem solving experts.

The mapping to and from the abstraction level is crucial, but also difficult to learn and apply. To circumvent this subjective and difficult to perform mapping, a methodology and algorithm are proposed that use fine-grained, automatically identified product concepts allowing to discover direct links between specific problems and related specific solutions, indicated by the light-grey arrow in Fig. 1. In the remainder of this chapter, these automatically defined product concepts will be called Products Aspects (PAs). The fine-grained PAs

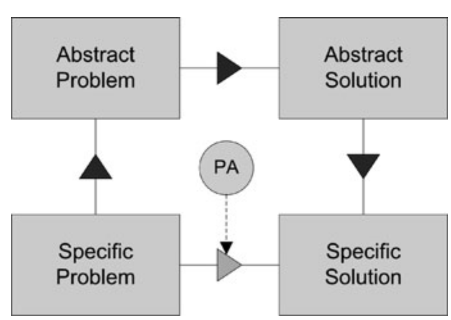

Fig. 1 Mapping between specific to abstract formulation

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will be shown to encompass product properties, functions and technologies.

This also exemplifies the link between TRIZ and design-by-analogy. Design-by-analogy is a methodology which enables the designer to find another product with similar (sub)functions. This solution is then mapped to the specific problem through abstraction. Since PAs encompass functions, the selection of these products can be accomplished through the PAs.

These PAs can therefore be considered as a basic framework for accomplishing, among others, the following semi-, or fully automated tasks:

- searching for properties, processes or technologies which can deliver a certain desired function, similar to the TRIZ *Function Database* [2];
- *characterizing products* to determine the current state of the product with respect to the relevant PAs;
- comparing products based on product characterizations to find *similar products* and support fuzzy front-end creativity and problem solving [3];
- *trend analysis* based on sequences of product characterizations [4];
- using, proving and updating the *contradiction matrix*;

In this chapter, the task of characterizing products is chosen as an example of the usefulness of the obtained PAs. This task can be regarded as the identification of the current state of the product in these PAs. As such, the results of these analyses are directly useful to assess the evolutionary potential of products along certain PAs, but also form a necessary basis for automated trend analysis, comparing products and searching for similar products.

It is noteworthy that the proposed methodology and algorithms are meant as a supporting tool or completeness check for designers, product developers and engineers. It can, however, not be the aim to replace *abstraction* as a central problem solving concept in Front-End Design or problem solving methodologies.

The remainder of this chapter is organized as follows. Section 2 offers an overview of related research on Product Functions and Product Properties. Section 3 describes the proposed methodology, and Sect. 4 presents the raw results of the PA analysis, while Sect. 5 illustrates the usability of the obtained PAs through the characterization of different products in PAs.

2 Related Research

2.1 Functions

Pahl et al. [5] describe the overall function as the intended overall relationship between inputs and outputs of a plant, machine or assembly, which is independent of any practical solution. This definition is similar to the TRIZ concept of Main Useful Function. This overall function can be broken into sub-functions forming a function hierarchy, which often resembles the component, or modular hierarchy for adaptive designs. From this, it is clear that from a practical point of view, (sub)functions of a system are often closely related to its components or building blocks.

These sub-functions can be provided by physical, chemical or biological processes, which in turn are realized by a working interrelationship between physical, chemical or biological effects, and geometric and materials characteristics [5]. In a TRIZ context, this can be interpreted as the function database, e.g. physical effects, and as the properties of the product or artifact [1].

2.2 Categorization of Functions

Pahl et al. [5] also developed a classification of functions and flows, in which functions are divided into 5 types, Channel, Connect, Vary, Change and Store. The flows are divided into three types, Energy, Material and Signal.

This classification was elaborated further by Stone and Wood [6], introducing a consistent classification scheme, the functional basis, which describes each product or artifact function in a verb-object (function-flow) format. Stone also explicitly states that this methodology contributes to several product design areas, including systematic function structure generation, comparison of product functionalities, and creativity in concept generation. These contributions are similar to the task list in the Introduction Section.

Another effort was performed at NIST, which developed a hierarchical taxonomy following the approach by Pahl et al. [5]. The NIST taxonomy provides a set of terms that are atomic, but also generic enough to allow modeling of a wide range of engineering products or artifacts [7].

Later, Hirtz et al. [8] reconciled and compared the NIST effort, the Functional Basis, the Systematic Approach of Pahl and Beitz (SAPB), a 6 function classification from Hundal [9], and TRIZ. Another comparison of TRIZ and SAPB can be found in Malmqvist [10], which proposes to restructure the vocabulary of TRIZ using the top level hierarchy of SAPB.

Although classical TRIZ only defines the concept of Main Useful Function (MUF), later additions or variants have included the concept of auxiliary or sub-functions [11]. Although not made explicitly, a function categorization can be found within TRIZ as the databases of effects, subdivided in Physical, Chemical, and Geometrical effects [1]. This database was later reorganized into a matrix format listing, with on the one hand different kinds of functions, and on the other hand a categorization of the object or flow into solid, fluid and gas. This database, the CREAX Function Database [12], was furthermore extended with more effects, and will be used as a reference for the results obtained from the proposed methodology. Therefore, in the remainder of this chapter, this database is referred to as the Function Database.

3 Proposed Methodology

The research proposes an algorithm and framework that, through analysis of term occurrences within patents, extracts information concerning product properties, product functionalities and technologies. The sections below each describe the different steps of the proposed methodology, an overview of which is also depicted graphically in Fig. 2.

3.1 *Random Full Text Patent Retrieval*

The EPO Worldwide Patent Statistical Database (PATSTAT) [13] used in this research is aimed at researchers and contains most patent fields, such as dates, citations, and abstracts. However, in its original form, the database does not contain full text descriptions. Since other research [14, 15] shows that the inclusion of a certain number of words of the description can be beneficial to text-mining in a patent environment, these descriptions are additionally downloaded and inserted into the database. Currently, the applied database contains around 155,000 randomly chosen patents with full text description sections, which are retained in full for further processing.

3.2 *Wordnet Filter*

In order to allow fast querying, the full text description of each patent is pre-processed, which encompasses a filtering step and stemming/linking step. The filtering only retains words occurring in Wordnet. Since Wordnet's vocabulary contains a large number of both technical and non-technical words in different spellings, this has the effect of eliminating only misspelled words.

The filtering furthermore allows retaining only terms with specific Wordnet categories, such as noun, adjective or verb categories. This is beneficial to storage or processing requirements, and also leads to less noisy results since the structure to be extracted from the data is mainly related to adjectives and verbs [3, 4, 11].

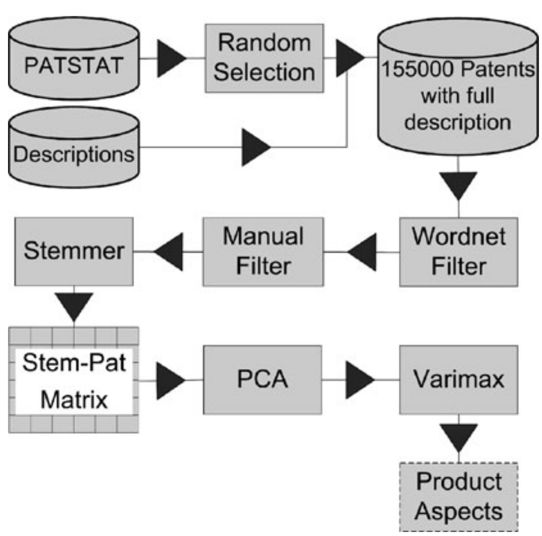


Fig. 2 Methodology flowchart

3.3 *Manual Filter*

To further reduce the noise level, all terms from the Wordnet adjective and verb categories which do not contribute valuable information about the structure or workings of a product are manually discarded from further processing. Table 1 shows 10 terms from this manual filter with their relevance. The relevance of each word X was determined by asking the question "If I know products A and B both do, are or have X, do I think it would be beneficial to look at product A to improve product B?". For instance, according to Table 1, the word "more" is not relevant, which indicates that if products A and B do, have or are "more" than this would not indicate a possible knowledge transfer between the products. However, from the same table, the word "roll" is indicated as relevant, which implies that if product A "rolls" this could indicate a possible knowledge transfer to a product B which also rolls, e.g. between car and train, we can imagine a knowledge transfer in the domain of aerodynamics or friction.

This manual filtering step reduces the number of terms to process by a factor of approximately three. This step however does not have a high impact on the structure obtained from the results, since it is not the specific terms that matter only their co-occurrence within the patents. The reasoning was validated by comparing the results with and without manual filtering, which clearly illustrates the same structure. However, the results obtained with manual filtering are

Table 1 Selection of words from manual filter

Word	Relevant?
More	No
Particularly	No
Roll	Yes
Operation	No
Become	No
Background	No
Cut	Yes
Length	Yes
Thereafter	No
Then	No

much more interpretable as a large amount of noise was cancelled.

3.4 Stemmer

The second pre-processing stage links each term to its stem obtained through the Porter Stemming algorithm, which in its original form does not account for English (U.K.) word endings, e.g. the word “materialise” has a different stem than the word “materialize”. In order to account for English (U.K.) spelling the words with English (U.K.) suffixes are manually adjusted to map to the same stems as their American English (U.S.) counterparts.

Furthermore, in order to facilitate the interpretation of the results by users of the system, all stems are represented by a term which was mapped to that stem, e.g. in the results shown to users, the stem “absorpt” is changed into the term “absorption” to facilitate reading and interpretation.

As a last pre-processing stage, each retained stem is related to all patents in which it occurs, and this information is stored in a table added to the applied database. This pre-processing allows fast retrieval in response to the queries in subsequent processing steps explained below.

3.5 PCA

The PATSTAT database is queried from MATLAB, and transformed into a standard term-document matrix format indicated as the Stem-Pat Matrix in Fig. 2. In this matrix, an element on row i en column j represents the number of times stem i occurs in patent j. This matrix is furthermore weighted with a Term Frequency Inverse Document Frequency (tf-idf) scheme [16] and normalized to account for different patent text lengths.

In a next step, certain Wordnet categories closely related to products, such as noun artifact and noun body, are discarded from further processing. This is done to bring out structure related to the properties and functions of products, and not structure related to products themselves.

The resulting term-document matrix is subjected to a Principle Component Analysis (PCA) [17], a technique closely related to Singular Value Decomposition (SVD) [18, 19]. This analysis allows extracting a given number of Principle Components (PCs), of which the first PC is the linear dimension oriented in such a way that it explains the maximum amount of the variance in the data set. Each succeeding PC represents as much of the remaining variability as possible, taken into account that all PCs are orthogonal to each other.

Before applying PCA, a term is represented as coordinates in the tf-idf weighted term-document matrix, in which each coordinate can loosely be interpreted as the number of times the term occurs in a document. These coordinates are expressed in correlated variables, as the number of times a term occurs in a certain document can be related to the number of times it occurs in other documents.

After PCA, all terms are expressed in a smaller number of uncorrelated variables or PCs, resulting in a term-PC matrix. For testing and analysis purposes, the number of resulting PCs is set arbitrarily to 300. In case this number would be increased, the first 300 PCs remain the same, but more variance is explained overall. Figure 3 depicts terms in a coordinate system formed by the second and the third PC. In this figure, different concepts can be manually discerned, of which “digital data transport”, “biological” and “compounds (dis)solving” are indicated with dashed ovals. As can be seen from this figure, the directions of maximum variance (PCs) do not coincide with the manually found concepts. This makes it difficult to interpret the meaning of the PCs. The techniques in the next section allow easier interpretation of these PCs.

It’s noteworthy that Fig. 3 only shows the terms with coordinates higher than the 99.6 percentile on both the second and the third PC. This 99.6% threshold is chosen arbitrarily, but set high enough not to encumber the figure by the number of terms displayed.

3.6 Varimax

Varimax rotation is the most used variant of all techniques aimed at rotating the PC coordinate system to a new coordinate system allowing easier interpretation of the resulting rotated PCs. For Varimax this is done through orthogonal rotation maximizing the sum of the variance of the PC loading vectors [20].

After rotation each term can be approximately described by a linear combination of few rotated PCs. By comparing the coordinates of a term such as, for example, “heat” in the original PC coordinate system in Fig. 4, with the coordinates of “heat” in a Varimax rotated coordinate system in Fig. 5, it can be seen that the Varimax rotation indeed allows terms related to “heat” to be interpreted in fewer components.

As can be seen from Fig. 6 compared to Fig. 7, each rotated PC contains fewer high value coordinates or loadings, and the directions of the rotated principle components coincide with the manually found concepts.

Therefore, the top terms of rotated principle component 38 in Fig. 7 all relate to “heat”, which is not the case for the top terms of the non-rotated “heat”-related principle component depicted in Fig. 6.

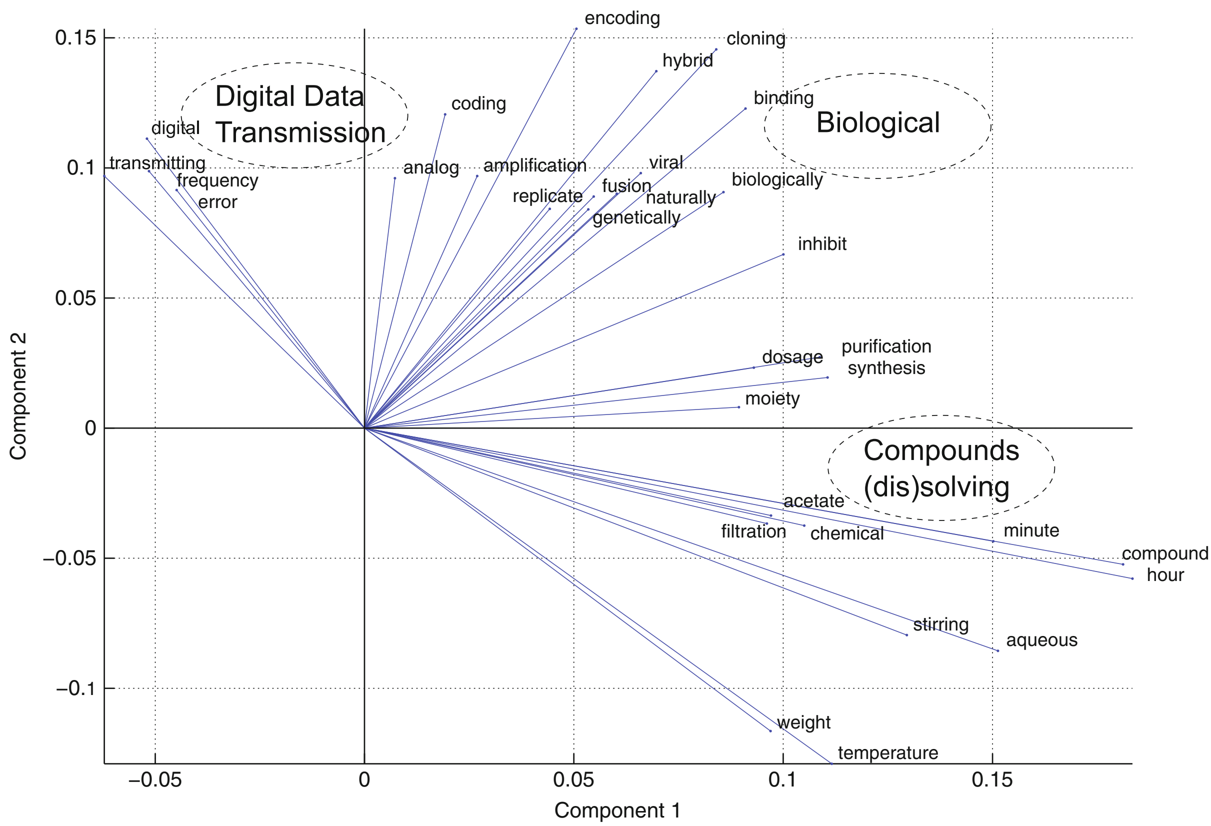


Fig. 3 Top terms in PC 2 and PC 3 with manual indication of involved concepts

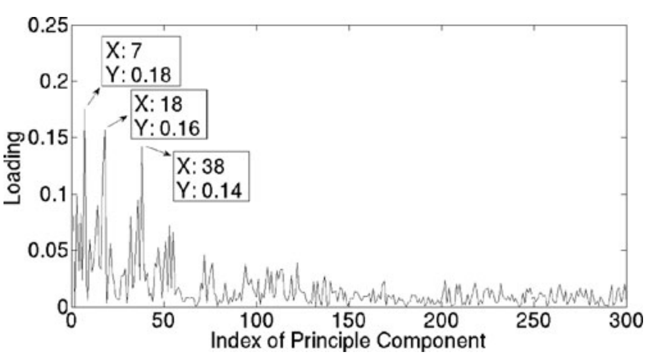


Fig. 4 Coordinates of terms related to "heat" in non-rotated PC coordinate system

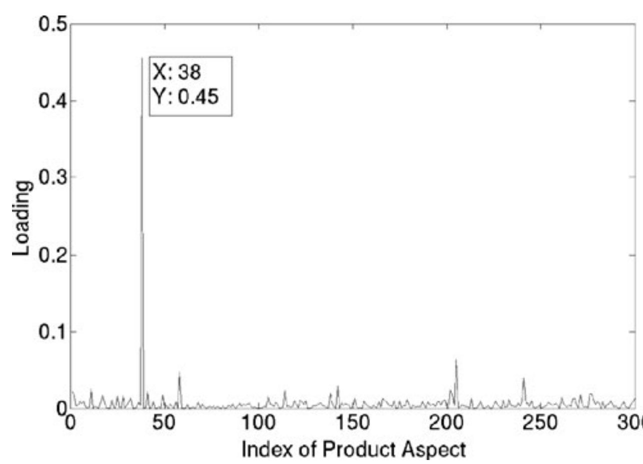


Fig. 5 Coordinates of terms related to "heat" in rotated PC coordinate system

As a result, the Varimax rotation is shown to ease the manual interpretation of the involved concepts because these concepts map to individual rotated principle components. In the sections below, these rotated principle components are called Product Aspects (PAs).

It's noteworthy that the rotated PCs are not ordered, and it is coincidental that one of the top principle components on which "heat" loads is the 38th PC, and "heat" also loads on the 38th rotated PC, depicted in respectively Figs. 4 and 5.

4 Results

4.1 Raw Results of PAs

Due to the high dimensionality of the results, it is not feasible to illustrate the overall results in one or more figures. For this reason, the figures in this section are mapped to a low

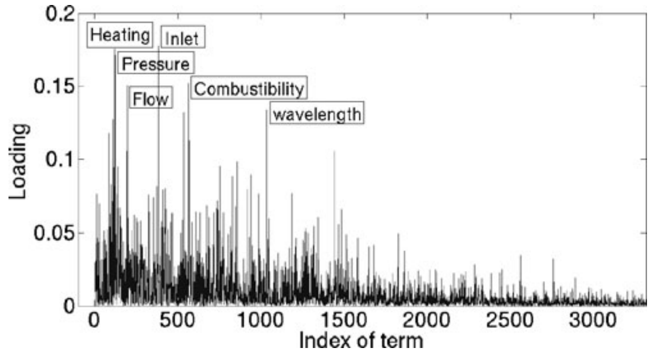


Fig. 6 Coordinates of all terms in the non-rotated principle component 7, which is related to "heat"

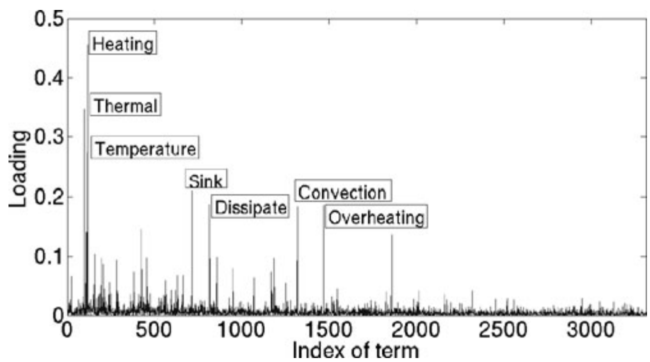


Fig. 7 Coordinates of all terms in the rotated principle component 38 related to "heat"

number of dimensions, or Products Aspects, e.g. the "heat" concept can be illustrated by inspecting only Product Aspect, or rotated principle component, number 38.

Figure 8, shows only the terms with coordinates higher than the 99.6 percentile on both the second and the third Product Aspect. This is a standard way to display the results of a PCA analysis, which clearly illustrates that Product Aspect, or rotated principle component, number 2 is related to the concept of "compounds and (dis)solving" through terms such as stirring, aqueous, filtration and compound. Product Aspect 3 is related to "digital data transmission" through terms such as coding, transformation, quantization, decoder and encoding.

Furthermore, a term with a high coordinate on a PA is said to be highly loaded on that PA, and hence is much related to the latent concept captured by that Aspect. Therefore, the approach proposed also allows to display terms in order of importance in a table-like format. This format is used in the sections below.

4.2 *Interpretation of the Results*

Table 2 illustrates the results of manually interpreting the first 10 Product Aspects through the analysis explained in the previous section. A more detailed version including the top loaded terms on each Product Aspect can be found in the Table 7 in Appendix.

From the analysis of the results, it can be seen that the proposed methodology allows extracting meaningful concepts from the global patent database. After manual interpretation, the concepts can be seen to encompass properties, functions, technology and application domains.

5 Product Characterization

This section illustrates the use of the resulting PAs as presented in Sect. 4, for automatically characterizing products.

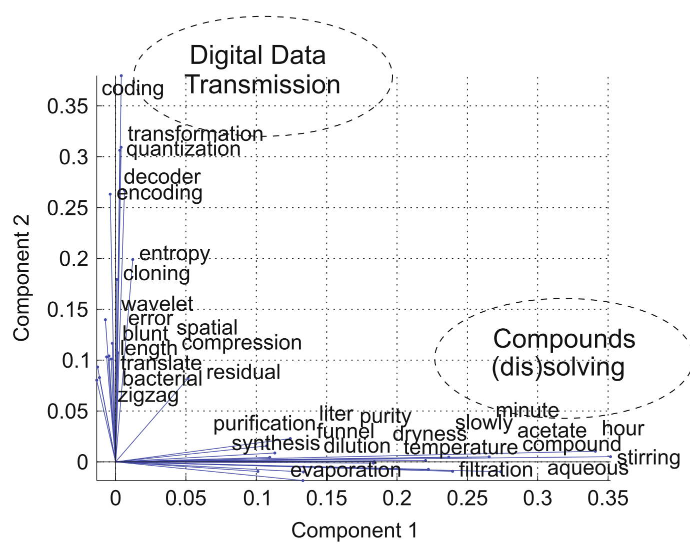


Fig. 8 Top terms in PA 2 and PA 3

Table 2 Manual interpretation of the first 10 product aspects

Number of product aspect	Interpretation of product aspect
1	Linear/volumetric dimension
2	Compounds/(dis)solving
3	Digital data transmission
4	Binding
5	Depositing/sputtering
6	Telecommunication
7	Hydraulics
8	Inflammation
9	Ball (and shape)
10	Corrosion

5.1 Random Selection of Example Products

Recently, different product taxonomies were developed as part of (semi-) automated product classification systems for use in, for instance, web stores or purchasing departments. Hepp et al. [21] highlights the properties of, and quantitative differences between common product categorization standards, such as eCl@ss, UNSPSC, and eOTD.

Another recently developed product categorization is the Google product taxonomy [22], which at the highest level refers to broad categories of products (Electronics, Home & Garden, etc.). The lower levels of categorizations specify these products further, e.g. *Electronics > Audio* or *Electronics > Audio > Audio Players & Recorders > MP3 Players*.

For the purpose of this research, the different categorizations can each be considered as a bag of products, from which a random sample of three products will be selected to illustrate the characterization of products. The Google categorization was retained as the basis to select a random sample of these three products because of the easy interpretability of the encompassed products and the relative small size of this taxonomy. The random sample was generated through the use of a random number generator on an enumerated list of products extracted from the Google product taxonomy. To ensure easy interpretability, these extracted 1,011 products were furthermore expressed into their singular form. Table 3 illustrates the selected random products.

Table 3 Random sample of products from the Google product taxonomy

Random number	Selected random products
915	Toiletry
182	Carburetor
173	Candle

5.2 Inserting the Products in the PA Space

The products from Table 2 are inserted into the space formed by the PAs, which allows interpreting each product in these different PAs. This is accomplished by querying the database, described in Sect. 3.1, and extracting the frequencies of occurrence of these products in each of the 155,000 patents. This can be represented as a product-patent matrix, which can be transformed into a product-PA matrix by applying the same transformations as were applied to the original term-patent matrix through PCA analysis and Varimax rotation (see Sects. 3.2 and 3.3). The resulting product-PA matrix represents each product in the PAs, allowing to characterize these products in the PAs.

5.3 Characterizing Products in PAs

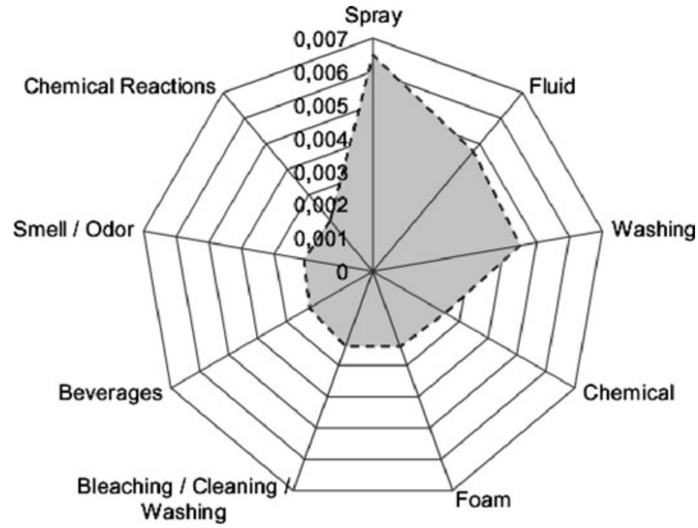
Table 4 below lists the top 15 PAs for the Toiletry product extracted from the complete characterization of the Toiletry product depicted in Fig. 10 in Appendix. The first 9 PA descriptions in this table clearly relate to the Toiletry product, and it is easily seen that PA descriptions corresponding to lower weight PAs relate less to the Toiletry product. This analysis can also be directly extracted from Fig. 10 in Appendix.

Similarly, the Table 5, and related Fig. 11, list the 10 most important PAs with their description for the Carburetor product. The fourth most important PA number 199 has no description because the interpretation based on the top terms occurring in the PA, was not sufficiently clear for the researchers. Similar to the Toiletry product, only the top 5 or 6 PAs relate closely to the Carburetor product.

Table 4 List of top 15 PAs for the product Toiletry

Order	PA nr	Loading	Description
1	148	0.0065	Spray
2	204	0.0047	Fluid
3	133	0.0045	Washing
4	22	0.0025	Chemical
5	295	0.0024	Foam
6	62	0.0024	Bleaching/cleaning/washing
7	292	0.0022	Beverages
8	219	0.0021	Smell/odor
9	172	0.0020	Chemical reactions
10	237	0.0019	Managerial qualities
11	5	0.0017	Depositing/sputtering
12	291	0.0017	Procedure/communications
13	131	0.0017	Tangling
14	277	0.0014	Rubber Specs
15	187	0.0014	Copying

Fig. 9 Radar plot of automatical characterization of Toiletry product



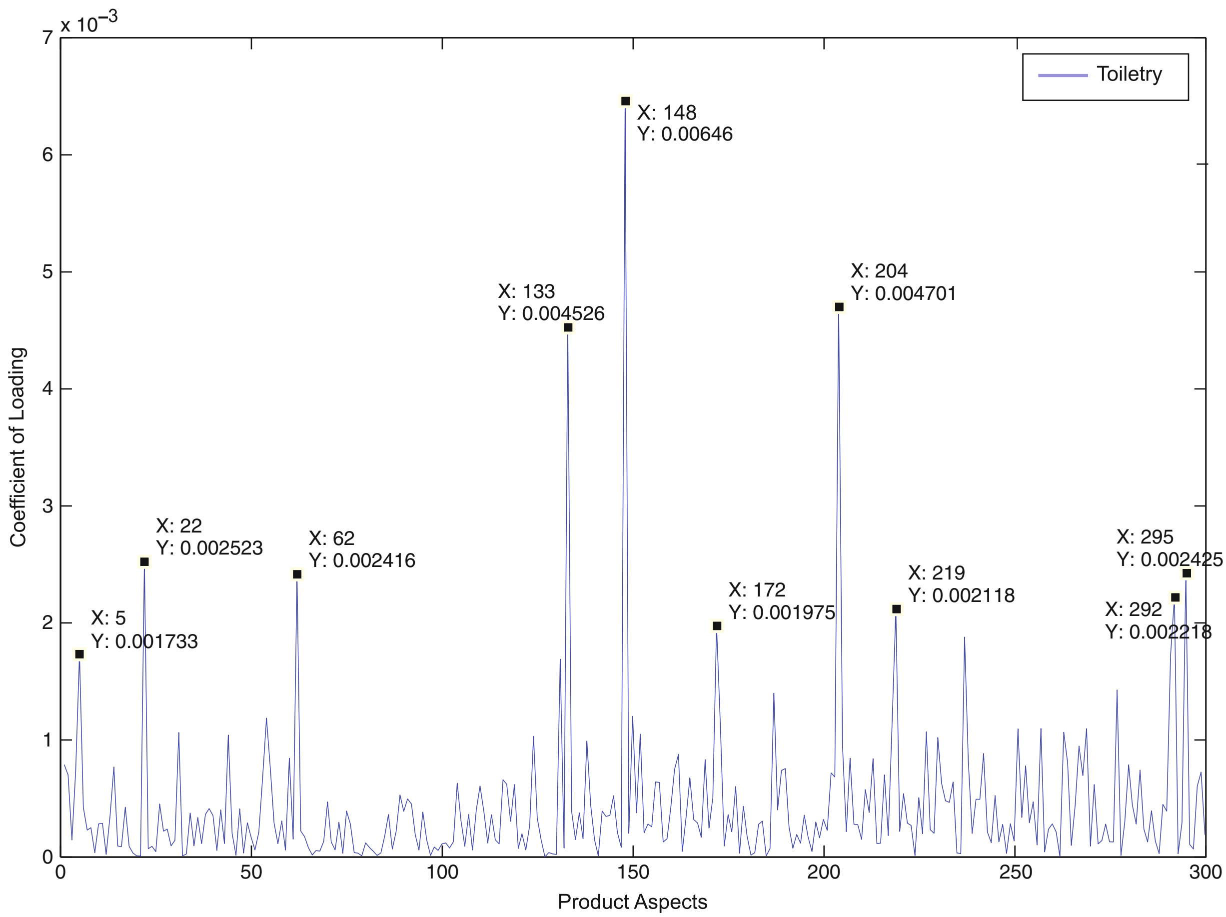


Fig. 10 Loading of product Toiletry on PAs

Table 5 List of top 10 PAs for the Carburetor product

Order	PA nr	Loading	Description
1	90	0.031	Combustion
2	109	0.013	Inflow/outflow
3	32	0.0054	Rotate
4	199	0.0046	–
5	125	0.0040	Aerodynamics
6	7	0.0039	Hydraulics
7	146	0.0037	Pronunciation
8	151	0.0030	Compress/decompress data
9	51	0.0028	Eye disorder
10	95	0.0027	Mechanical structures

Table 6 List of top 10 PAs for the candle product

Order	PA nr	Loading	Description
1	36	0.073	Fire/burn
2	298	0.029	Protect/damage/strike
3	38	0.021	Heating/cooling/temperature
4	250	0.020	Explosions
5	90	0.017	Combustion
6	125	0.015	Aerodynamic
7	223	0.014	–
8	205	0.013	Humidify
9	219	0.013	Smell/Odor
10	138	0.013	Sintering

Table 6 lists the same information for the analysis of the Candle product. In this table, the seventh most related PA with number 223 was not easily interpreted by the researchers, and its description is therefore empty. Once again it is clear from the table and the related Fig. 12 in Appendix that the top PAs relate closely to the Candle product.

The automatically generated product characterizations based on the proposed methodology, can also be graphically depicted through the same radar plot visualization introduced by Cavalucci [23] for the TRIZ laws of development, and by Dewulf for more specific trends [11]. Figure 9 above depicts the product characterization of the Toiletry product through this type of visualization based on the top 9 of the sorted list of PAs in Table 4.

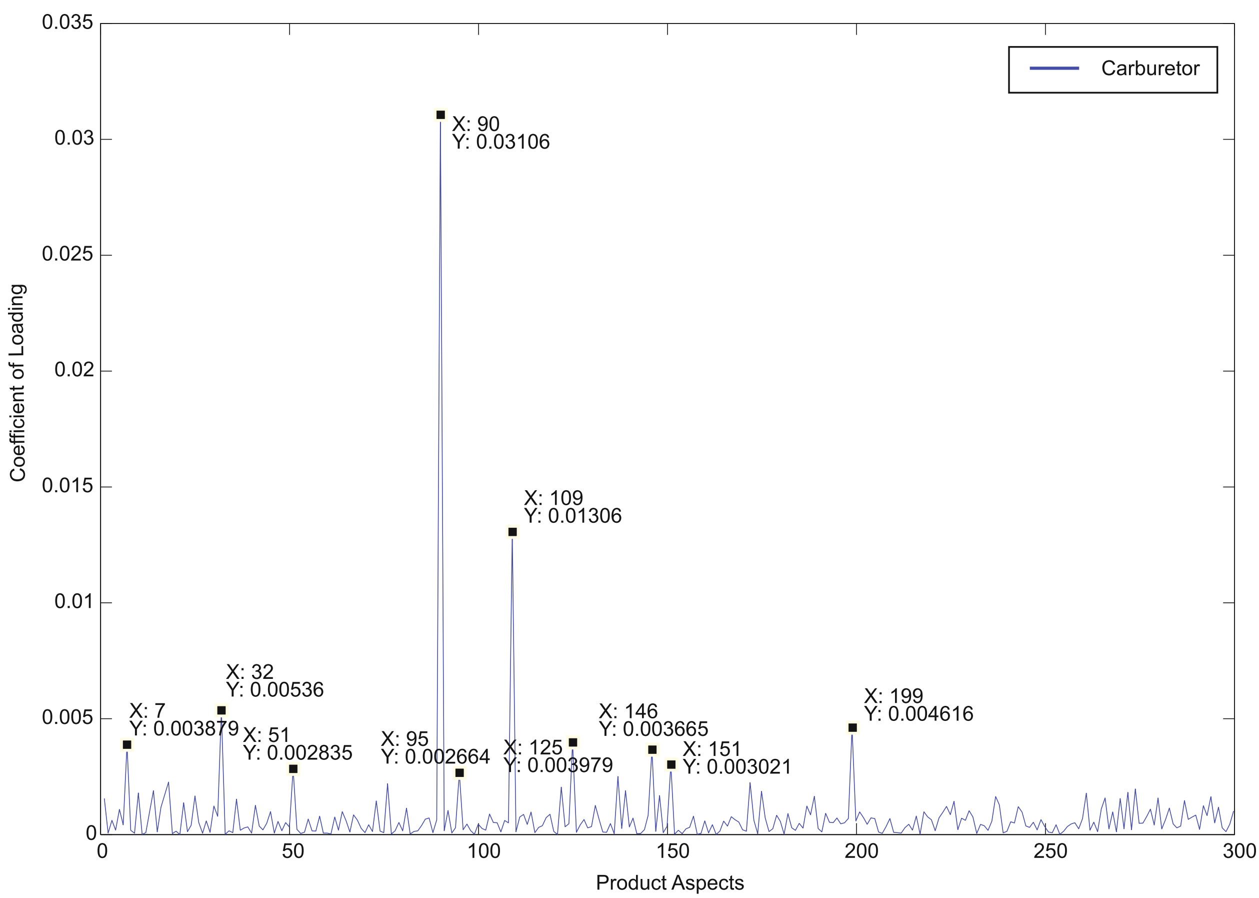


Fig. 11 Loading of product Carburetor on PAs

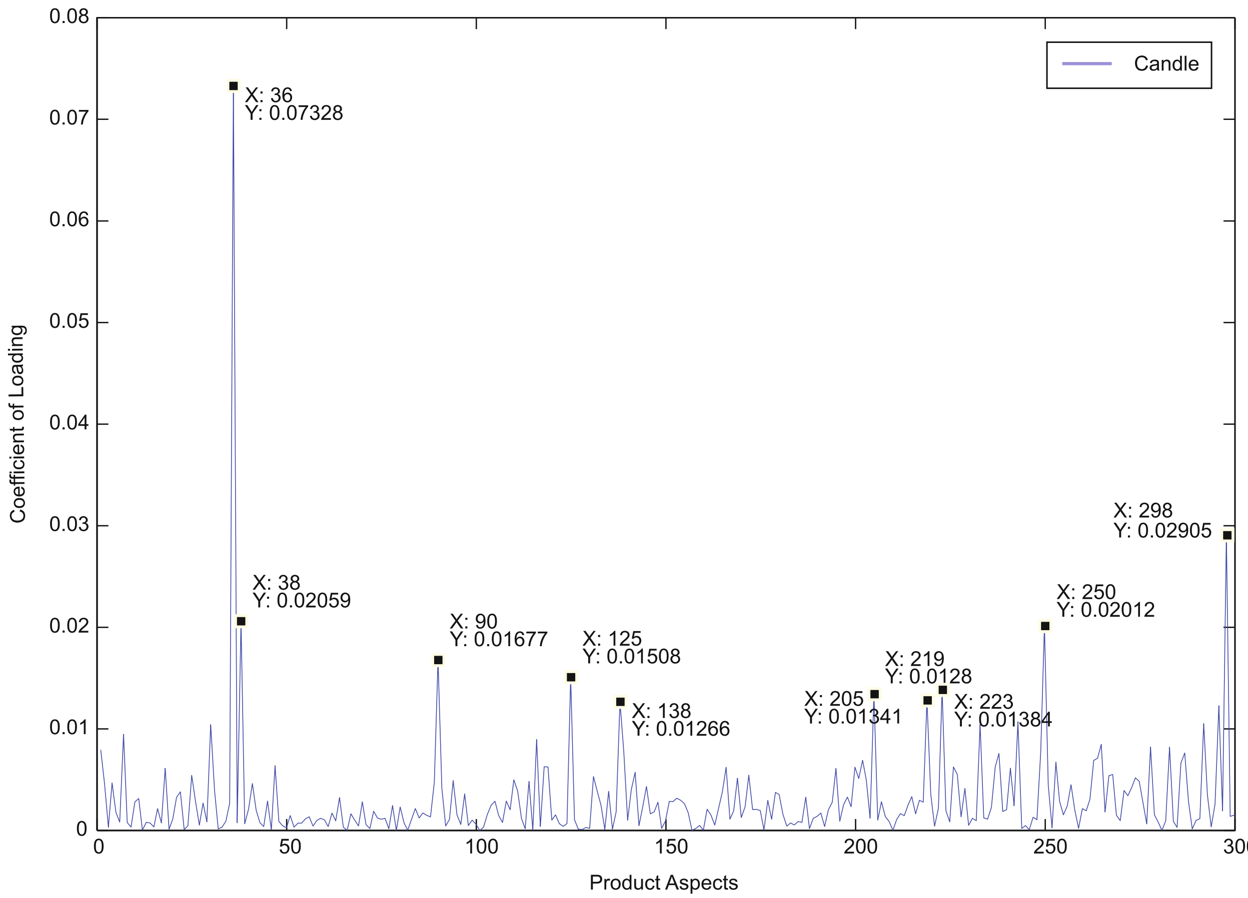


Fig. 12 Loading of candle product on PAs

6 Conclusions and Further Research

It was shown that text-mining allows extracting meaningful structure from patents through the analysis of the occurrences of words from specific Wordnet categories. The results of this analysis can be interpreted as fine-grained product dimensions, called Product Aspects. As illustrated for a number of examples, most of these Product Aspects can be easily interpreted by humans through the top terms occurring in these Product Aspects.

It was furthermore shown that Product Aspects encompass properties, functions and technologies, and that these Product Aspects can be related to products, which allows for automated product characterization. The proposed product characterization methodology is in itself directly usable as an automated technique to identify products with certain properties, functions or even products using certain technologies.

In a TRIZ context, PAs can aid in identifying specific products to supplement the abstracted solution in TRIZ tools, a process which is currently executed manually. The product characterization is furthermore a needed step for a range of additional functionalities, such as evaluating the evolutionary potential, comparing products, searching for similar products and trend analysis, as will be documented in further publications.

Future research will also concentrate on testing the effect of this methodology on design-by-analogy case studies and market development in an industrial application.

Appendix

Table 7 First 10 PA with top 5 terms

Number	Description					
1	Linear/volumetric dimension	Inch	Centimeter	Millimeter	Square	Micron
2	Compounds/(dis)solving	Blend	Fraction	Hydrocracking	Cracking	Separately
3	Digital data transmission	Coding	Transformation	Quantization	Decoder	Encoding
4	Binding	Binding	Fusion	Naturally	Transient	Biologically
5	Depositing/sputtering	Deposit	Sputter	Thickness	Uniform	Annealing
6	Telecommunication	Service	Forward	Mobility	Cellular	Redirect
7	Hydraulics	Pressure	Hydraulic	Cylinder	Pneumatic	Inlet
8	Inflammation	Inflammation	Orally	Inhibit	Dosage	Prevent
9	Ball (and shape)	Decahedron	Kickoff	Punt	Oversimplifica	Kick
10	Corrosion	Anion	Cation	Coalesce	Decortication	Proton

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Metrics and Benchmarking, Performance Evaluation for Global Product Development

Towards a Quality Referential for Performance in Design

A. Poulet, B. Rose, and E. Caillaud

Abstract The current competitive environment push companies to take actions to improve their activities, regarding whatever their products, processes, or their organization. But how to intervene? Which could be the best measures and practices that will optimize the system performance? Also in the goal of greater overall efficiency, we evaluate the performance of collaborative design projects; we create indicators, which can drive us in the best interests, in regard of our objectives. But are they well adapted or well integrated regarding the needs of interfaces, between the company and the assessment system itself? To lay a solid foundation of the evaluation process of performance, we take as the basis the normative approach in design management, the standard ISO or AFNOR to introduce our notion of performance.

Keywords Collaborative design · Performance · Quality management · Design activity management

1 Introduction

In a difficult economic environment, improving the competitiveness of a manufacturing company has to be done especially by improving the performance of his R&D department and his product development service. The search for performance in these areas may lead to innovations in the product itself, but can also affect the engineering and organizational management processes. In the specific case of routine product design, the implementation of a repository for performance management in the design activity can be a decisive advantage [1]. However, a number of requirements from quality benchmarks or specific references in the company already exist. Our research work specifically focuses on this axis and aims at providing a reference frame combining the advantages of a quality system while incorporating a performance management system for the design activity. The present works have been realized within the framework of the CODEKF project [1–4]. This project has been labeled by the French automobile competitiveness cluster "Vehicle of the future" in *Alsace* and *Franche-Comté* areas in the east of France. This project is mainly focus on firms that are for the majority in the considered market area: rank 1, 2 or 3 subcontractors [5] of the automotive industry but the results of the present article can be extended to every design situation. This article specifically focuses on the quality requirements related to product development and offers a bibliographic positioning regarding the concept of performance in product design management. The positioning and the analysis of normative literature leads us to introduce a repository model to management the product design activity named "CodeSteer" (for Collaborative Design Steering) and the specifications of the software application based on this model.

2 Performance in Design

2.1 Performance and Semantic

First of all it seemed necessary to us to clarify the semantics relative to performance and to explain how to represent performance. In the literature, performance is considered as a search for optimizing the relationship between the input and outputs of a system, with the purpose of achieving a fixed objective [6]. Performance has to be measured within a referential, and is a differential between an activity at a time T and T+1. It allows to compare internal and external elements of its own system or referential [7]. The notion of performance takes place in an identification of elements bound to a referential. For our purpose, regarding the design context, this referential will be the project which will be attributed

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to it. Performance is necessarily a notion that arise from a difference, that cannot be described without beforehand establishing a scale [8]. A certain amount of works has been carried out over the last twenty years in the field of performance management with the emergence of various models, frames of studies and ground studies led by industrial or academic researchers. However the concept of performance seems pretty ambiguous [9]. So, according to [10], the performance measurement is a subject which is often discussed but rarely defined. However, some attempts at definitions have been proposed [11, 12]. We will consider in this context the definition given by [10] which proposes performance as a quantification of the effectiveness and\or the efficiency of an action or activity.

In the field of performance assessment, looking at the design activity, the difficulty is to make the difference between the performance of the design activity and the performance of the design management activity (Fig. 1). The purpose of the design is to answer the expressed needs and to optimize the artifact, whereas the purpose of the design management activity is to manage and improved the output of the activity itself [13]. They cannot be separated, but the way of managing them will not be the same for each one.

2.2 Why Performance in Design?

Design choices determines 75% of the quality and the costs of a design project [14]. In economic terms, one speaks about 90% of the costs engaged at the end of the design for only 10% of cumulated real expenditure.

The design activity has a strong evolution due to these reasons. This evolution takes the form of an optimization when it comes to the development of the design in its planning or in its management.

If we take into account the fact that the main part of the defects are made at the design stage, it is obvious that the design management activity is a mean of reducing these defects.

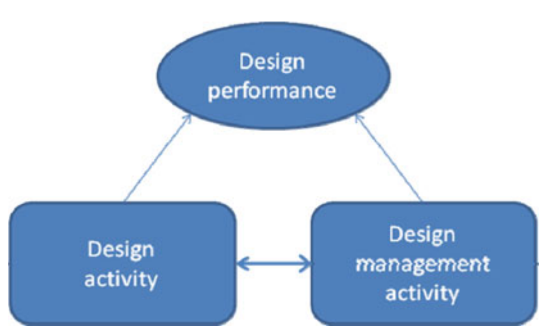


Fig. 1 Performances relationship in design [13]

2.3 Effectiveness, Efficiency, Relevance

In performance assessment, there are three measurements which constitute the triptych of control in management [6]. These measurements take place in the decision-making system and in the project steering. They are intrinsic measurements of performance.

- Effectiveness is the measurement of a difference between the results and the objectives. If the system's effectiveness, which can often be found through indicators of quality, is not satisfactory, actions will take place on the internal organization of the system and the various settings available.
- Efficiency is the measurement of the difference between resources and results. Efficiency is mainly found in the operational phase of the system or project, and the decisions to be taken for greater efficiency will be in the scope of monitoring.
- Relevance is the extent of the gap between the committed resources and the objectives. The relevance shows the feasibility of a project and the level of satisfaction that can be obtained. (Fig. 2)

One should not forget either that these measurements are taken in a dynamic logic; they are dependent on time and thus on the advancement of the project. These measurements must be set with regard to this dynamic vision.

2.4 Performance in Production and Difference with Performance in Design

In production, the performance is mainly related to the product, the artifact or the object that meets the needs.

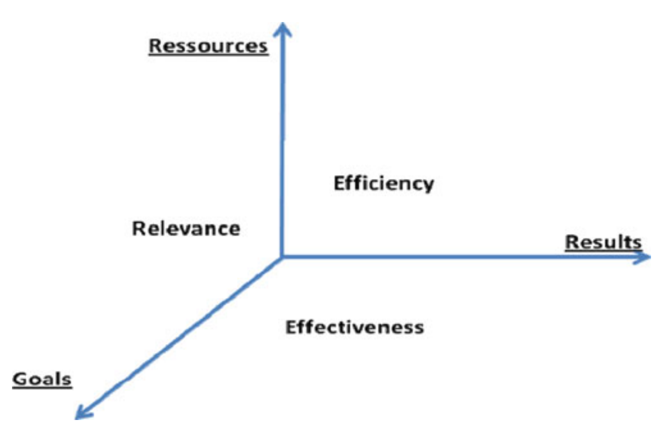


Fig. 2 Triptych of management Goals/Results/Ressources [6, 15]

Table 1 Comparison of manufacturing and product introduction [13]

	Manufacturing operations	Product introduction
Similarity between processes	Very similar	Dissimilar
Number of times the process is performed	Many times	Once
Time-lag for mearuring output	Weeks	Years
Ability to measure output	Directly measurable	Indirectly measurable

It manages the production system to give the object, as much quality as possible or try to bring its ideal case. It is clear at this point that, when the product is defined, that which will determine the product will be the company policy will, the company politics in terms of cost, quality, and period [16].

The analysis of production performance depends largely on operational measurements such as the number of produced items or the number of faulty parts, that are purely physical data [17]. This is an aspect that is more easily defined and understood. Unlike production, the design activity requires a greater degree of abstraction, conceptualization, comprehension, problem solving, experimentation, sharing and collaboration (Table 1) [18]. Many authors have recognized the difficulties of understanding the design performance [19–21]. These difficulties result from the abstract nature of the data, that may emerge from the design work: knowledge in a large number of very different domains, the time amplitude which is bounded tothe design activity, the unclear definition of measurements, and the design objectives.

3 Modeling Performance in Design

A literature review laid on the specific field of performance in design showed us that there are only few models and formalism dedicated to performance in design. We present here 2 models that could fit such ambition.

3.1 Existing Models on Performance in Design Management

3.1.1 GRAI Model

The reference model GRAI (Fig. 3) is used to model a system, whatever it is and, as a consequence, it is also adapted to model a design system and is quite appropriate for the study of design activity performance. It indeed separates the operational part (technological system) of the steering part (decision-making system) to facilitate the modeling and the understanding. The technological system is divided into autonomous organizations (called design centers) in a coordinated structure. This will provide answers about the steering of technological system. In the GRAI model, each decision center is autonomous within the framework of a hierarchical structure. Synchronization and coordination between the different design centers are provided at the decisional level and modeled using the structure GRAI-R&D. This is usable in product design but it can be generalizaed for the design systems [22].

In the same stream, the work of Girard and Robin [22] focuses on the study of a methodology and a model of design performance assessment for the steering of design systems. Their model for the design systems assessment in a multi-stakeholder, multi-disciplinary and multi-projects presented, allows the inclusion of performance factors in design. This model positions the design performance system in an overall

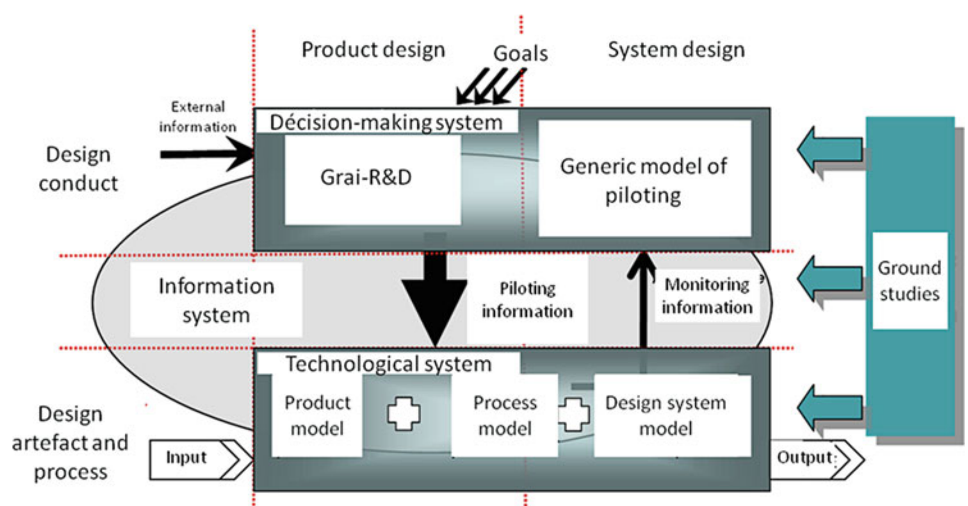


Fig. 3 GRAI model

consideration of internal and external environments, scientific and technological knowledge, and actors in terms of Product, Process and Organization aspects. An implementation of the assessment model is effective through a modeling methodology, monitoring the business and design system. This methodology is built around the methods GIM, GRAI and GRAI R&D.

3.1.2 The O'donnel and Duffy Methodology for Design Performance Modeling and Analysis

The O'donnel and Duffy methodology is based on the principle that performance in design is formally different from the production performance from the characteristics of non-repeatability, novelty and the fact that it is based on the heritage of more tacit than explicit knowledge.

The formal modeling of the performance of O'Donnell and Duffy is composed of four models and approaches. This constitute the PERFORM system (Fig. 4) [13].

- The E^2 model (Efficiency and Effectiveness) which describes the nature of performance at a fundamental level. This model is based on a knowledge processing view of design. The input knowledge is transformed during the design activity via the use of knowledge resources to create output knowledge or new knowledge and under the direction of goals. Effectiveness and efficiency describe performance in any situation and these are distinguished and related within the model.
- The DAM model, which distinguishes design and design management activities within a managed activity. Design activities are aimed at achieving design goals while design management activities address design activity goals. From this model it is possible to distinguish effectiveness and efficiency further in terms of design and design management.
- The PMM model, which describes the process of measuring and managing performance within a managed activity. Design and design management effectiveness are measured and provide key information in support of controlling decisions such as resources allocation, changing goals, or stopping the activity.
- The resource impact model illustrates the influence of resources on performance. This model shows us the weight and impact of each of the resource compared to each other.
- The PERFORM approach provide a structured process for analyzing design development performance and identifying the best means by which it may be improved.

3.2 Limits in Design Performance Modeling

Many process models have been studied in the literature on product design [23, 24].

However, we can note an overall lack of references in relation to the concept of performance itself. O'Donnell and Duffy outline a few attempts that take into account different models of process developed in the 1990s. The elaborated models have however most of the time a border relatively badly defined between what is related to the performance of the design management activity in itself and what is related to the performance of the design activity and the artifact. Most of the time, the performance listed in the scientific works concerns the product performance and the artifact itself in specific areas [25].

The O'donnel and Duffy model, as well as the GRAI model, however take into account this essential differentiation, to consider the intrinsic performance of the organization and design teams, without mixing the characteristics of the product designed. The Girard and Robin model

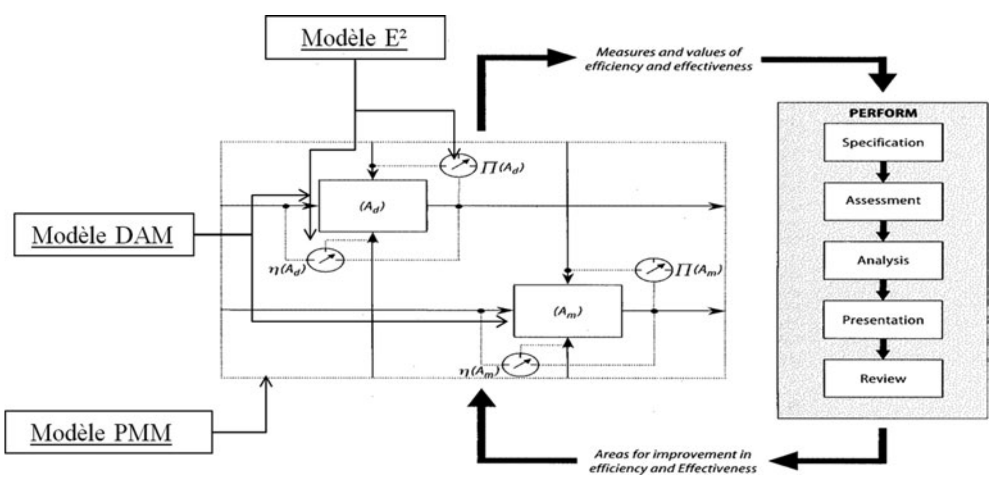


Fig. 4 *PERFORM*, methodology for design performance modeling and analysis [13]

also allows this differentiation between local and global objectives [22].

However, the problem with these various models is their relatively non-experimental and non-use in a real industrial framework. Indeed, any research in the field of design aims at promulgating results, in other words approaches, methods, models and tools, which could improve the performance of the design activity. However, the relationship between the use of these methods, models and tools and the real improvement of design performance in their implementation in industry is rarely demonstrated.

The integration and the choice of parameters or indicators which were selected must be accurate to allow greater clarity in the design management. Therefore, standardisation of the performance evaluation process might be the solution. Regarding the normative literature, this should be undertaken by following norm exigencies. In the next sections, we examine the quality systems for design management.

4 Quality for R&D Departerment

4.1 Practice for the Design

Quality in Design project had been treated in various norms and in some research papers. We present here a synthesis of those works.

4.1.1 Existing Standards

In concern of the product design, the usual requirements in term of quality management are in the norm ISO 9001, 2008 [26] chapter 7.3. The standard show us the important steps to follow, for designing and develop a product.

- Planning Design and Development
- Definition of input elements of the design and development
- Definition of output elements of the design and development
- Design review and development
- Verification of design and development
- Validation of design and development
- Control of design changes and development

However this standard doesn't define the explicit information that has to be present at each step of the design project.

A french standard [27] named *process control design and development* specifies three particular steps of the design process.

The first one is the control design that includes guiding the process design and management of design projects. To control this process we should determine:

- The different states of the process,
- Management of the activities associated with each stage to ensure optimum operation,
- Checkpoints ensuring the specifics ways of carrying out such monitoring and the measured criteria,
- Activities and their interfaces,
- Documents related,
- Databases and software developed or used during the execution of design activities.

The second step is the design process development:

The design process developement can then be divided into five phases:

- The specifications of the needs,
- The capabilty of the organization to perform the design,
- The choice of the solutions to be developed,
- Detailed study of selected solutions,
- Validation and acceptance of solutions.

The third step is the modification of the design or Redesign : this step establishes that any change occurring in documents or databases must be analyzed to evaluate its justification and impact on product realization; specifying actors, documents, times and reasons for the changes. ISO 9001 version 2008 with its Chapter 7.3 and the standard FD X 50–127 are the two main standards at international and French level that apply specifically to the design activity and design process for its control. They are mainly related to aspects of planning the design activity. These standards are low detailled and do not refer to a system of performance evaluation in the specific field of the design activity. In the next paragraph, we have therefore strived to study the research works that have undertaken to bridge the concept of Performance and Quality in design.

5 Performance and Quality

5.1 State of the Art in Performance and Quality in Design

While studying performance and quality in the design field, we can notice various aspects. In this study we resumed the main themes. They are divided into four categories as shown in the (Fig. 5):

Fig. 5 Performance and Quality in the design field

We will focus here only on two categories: "quality performance and knowledge management" and "the concept of quality and design management":

- The quality system performance and knowledge management category describes how the system generates knowledge within the quality system [28, 29]. Furthermore it demonstrates the relevance of this approach for companies that primarily generates and manages this knowledge, knowing that the performance increasing is in the managing of this knowledge.
- the second category includes a large number of scientific papers on quality and design management. In [30] the author shows for example that the management of the design process allows higher quality performance whether internal or external. A structure for the synergy between these different methods of management which are very different depending on their strategic alignment within the company are also presented. [31] in order to address the quality in terms of designing the quality system beforend, the authors show its influence on quality performance.

The concept of quality in the design process is addressed in some research, however, a number of questions remain suspended in this field. We show in the next paragraph some of the gaps existing while dealing with performance in design activities.

5.2 *Questions and Gaps Regarding Performance and Quality in Design*

Performance management practices, such as performance appraisals, are often considered to be incompatible with the principles of quality management. But if designed appropriately, performance management systems could support rather than hinder quality. These past years, organizations view performance management as the successors of management by objectives or MBO. They see performance management as a key system that can promote and sustain good initiatives such as business renewal, and quality management [32].

Deming [33] and others argued that performance system management is not compatible with the quality management. The main issue was that performance management was too focused on individual characteristics rather than on system factors. The quality perspective questions the emphasis on individuals rather than on aspects of systems as being relevant to work performance. In response to Deming's admonition, a number of scholars countered that traditional performance management practices could be customized to support quality. The debate resulted in several prescriptions for adapting performance management system components to the people requirements of quality. Whether or not this abundant advice resulted in new performance management configurations in quality-driven organizations remains largely unknown as scholarly work was directed more at developing conceptually appealing alignments than at validating them.

In our literature review, we noticed that the subject of the performance of collaborative design and quality is not addressed from the perspective of performance management design in a quality system. The interest of designing the quality is to establish a benchmark and standard for improved performance of the quality system [31] and performance of the company and its system production [34]. The explicit use of the quality system as defined in [26, 27] for managing the design project will affect the performance of the design.

The literature offered advice but failed to address the need for research findings that elucidate key alignments between quality and performance management. This, we argue, is problematic on both theoretical and practical grounds. First, a lack of empirical evidence casts doubts upon the validity of theorizing in the area of strategic human resource management. A demonstration that performance management systems correspond in hypothesized ways to a quality emphasis would provide suggestive evidence that organizations are indeed linking their performance management practices to broader environmental variables. Second, from a practical standpoint, empirical evidence of an alignment would suggest that performance management systems can be compatible with quality, a proposition that in itself remains widely disputed. Such evidence would further point to the strongest and weakest links between quality and performance management system design features [32].

So through a real alignment of the quality and the performance management system, we can produce a greater performance system. Then for managing design performance we know that we have to take a system or an organisation in its global view, keeping in mind the tryptich of management goals/results/ressources.

There are many tools and models in quality management and project management, but in general these tools are very general. In fact, these tools do not effectively measure the performance of design project. The view of the performance in the ISO 9001 was revisited in his 2008 version as shown in [35] but is still too broad for the context of management of the design process and does not accurately respond in terms of relevant parameters for these activities.

In the next chapter, we show our model of performance evaluation in collaborative design project.

6 The "Codesteer" Model: A Static Framework For Performance In Quality Driven Collaborative Design Project,

Here we present our model "CoDeSteer" (Collaborative Design Steering) incorporating both the concepts of quality and performance management for collaborative design of manufacturing products.

Our class diagram incorporates the approach of modeling the project after IPPOP [36–38] by including an explicit reference to formalize the process under a quality approach. We chose UML because of its capacity to be a technical language used by developers. This language of technical communication allows us an easy translation in terms of computer specifications of our approach. Thus the model is a basis for a computer application. Here we explain the concepts presented in the UML class diagram in (Fig. 6).

The Resources class is composed of the three resources in a project design: information resources, human resources and material resources. In the different quality procedures that are used within the project management of design, resources must imperatively be present from the beginning of the project. As presented in [26, 27], information management is essential from the beginning of the project.

The Framework class represents the reference model of the standard. It is in this class that will formalize the project according to the quality standard used for managing the project design. It will also incorporate the performance indicators specifics for each hierarchical level of the project.

The class collaborative project is the specific informations of the current project.

The Data Product class is the class for all the various informations that will be generated during the project. It allows, by the values of the different performance indicators to steer the design activity.

In a dynamic point of view, this model is based on the Demings wheel "plan, do, check, act". To do a performance evaluation we need a strong referentials, that's why the ISO 9001[26] and the AFNOR 50127 [27] standart were taken. Those standart give us a guide for the process of design project. This lead to a standardized process of design project.

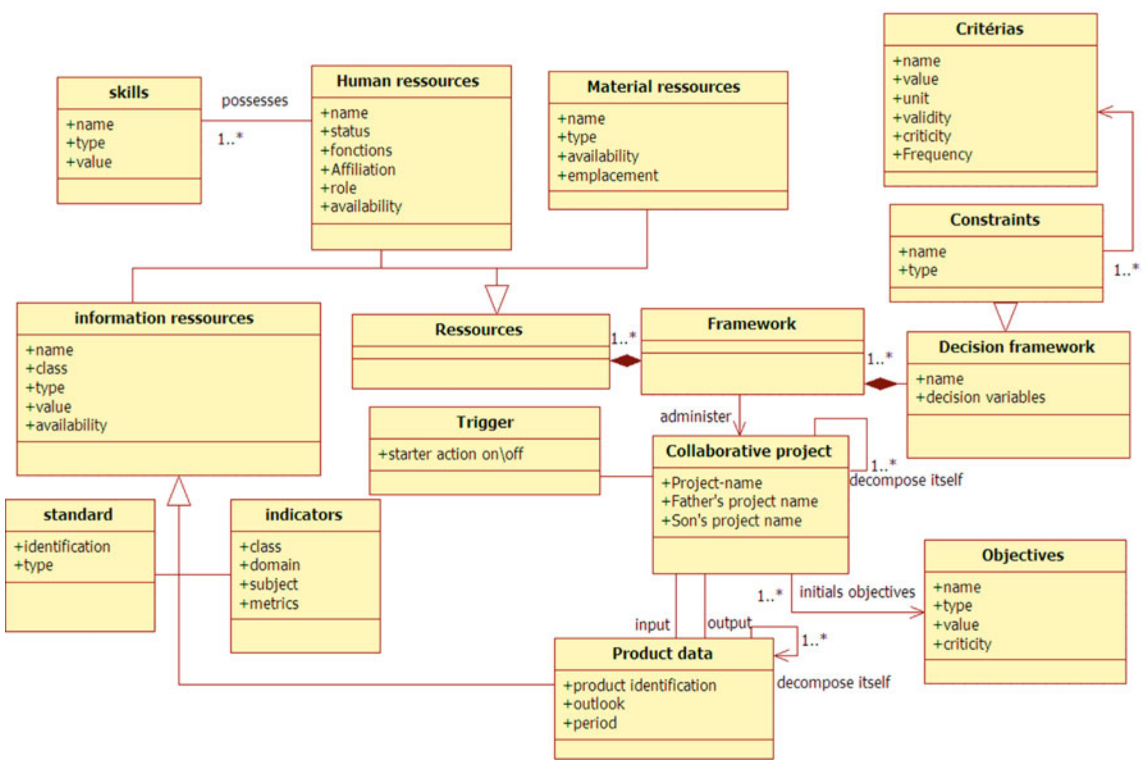


Fig. 6 Class diagram of the CoDeSteer model for performance in the design process

Every project subdivided itself in subprojects or activities. Each activity will have his pool of indicators, objectives, and constraints. With this, the first step of the demings wheel "plan" is done. Then the project begin, this will create product data this step is the "do". Then the project is in one of his review, so we can confront the data with the indicators and the objective, this will give us the performance of our projects, this step is the "check". After this step we can recognize the part of the project whith good or bad performance thus we can "act" to get a better evaluation on the next turn of wheel.

The codesteer model intagrate the standards class, this class is to make a referentials for the guideline of the design process. This completed guideline will make a database of old projects, that will be reference for making new project, if the activities are alike.

The next chapter is an explanations of the software interface of the CoDeSteer model.

7 Software Fittings and Explanations

7.1 Graphical User Interfaces Presentation

This application named "CoDeSteer" Collaborative Design Steering is a software composed of two graphical user interfaces, an interface for operation and consultation, and an interface for editing the projects specifics.

7.1.1 Specifications of the Operating Interface:

The interface operation (as shown in Fig. 7) consists of a Dashboards that are built into an existing interface or used independently. Their selection is made based on user rights and specific topics.

7.1.2 Specifications of the Design Project Editor

This editor must allow the creation of dashboards in the technology "what you see is what you get.". Its interface should provide all the tools necessary for creating and editing Dashboards. The publisher has the appearance of the diagram in Fig. 8.

7.2 Technical Specifications of the CoDeSteer Software

CoDeSteer is a software is based on a client/server (3 tier) architecture. The client application will be used "in line" from a web browser. The basic software is developed on the platform .NET platform. The publishing and the use of the Dashboards will be made in .Net technology and developed with an Application in JavaScript. The software components will provide interfaces for their integration into CoDeSteer. These interfaces are mainly sources for database, rights management, topics management and dashboard containers.

7.3 Functional Specifications of the CoDeSteer Software

The software CoDeSteer is composed of several modules. Each module has a series of specific activities. The main objectives supported by these modules are:

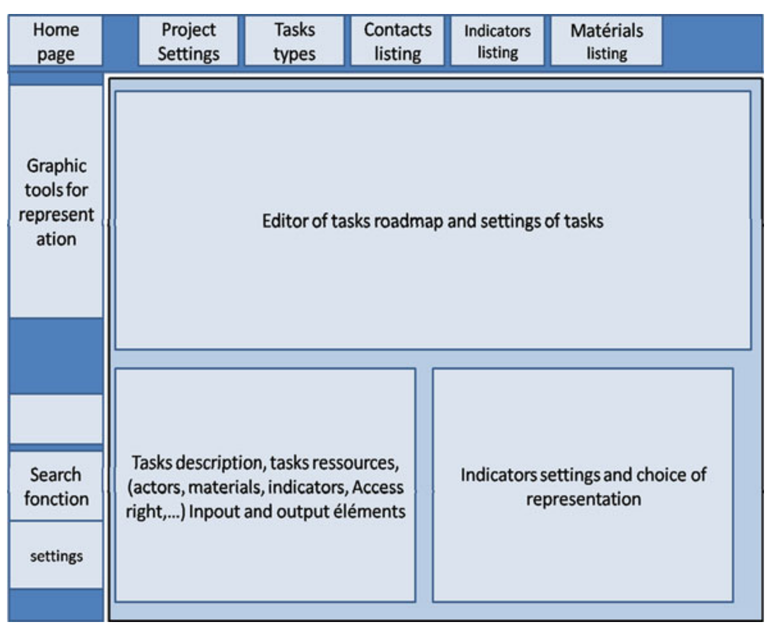
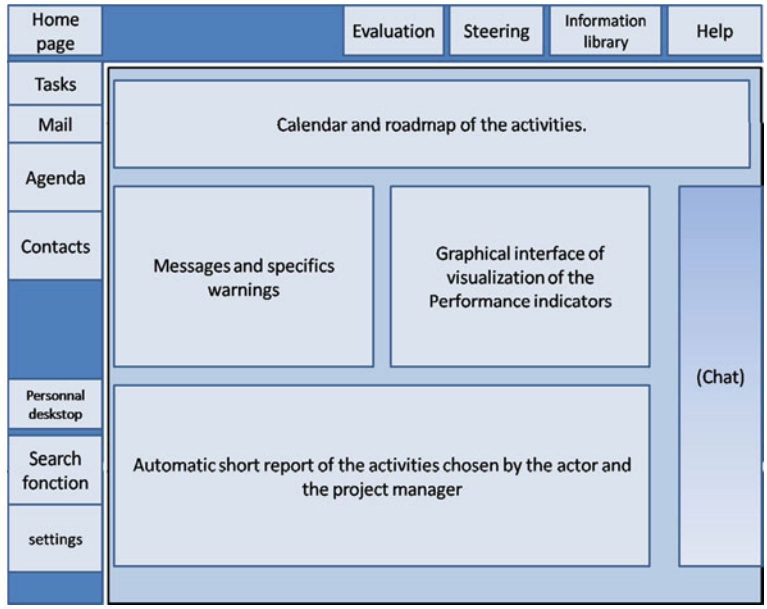


Fig. 7 Sample of Graphical User Interface for design project editing

Fig. 8 Sample of Graphical User Interface for design project steering



Planning:

- Planning Management, roadmapping, milestones editing
- Testing and evaluation of design project planning (best road to accomplishment).

Project design:

- Development of a design project.
- Validation of design steps
- Management review stages of design.
- Specification of inputs and output of each project and each task. The specific performance indicators are chosen at this point.
- Control of changes in the design or re-design.

To provide clarity and relevance to the different software modules, a visual dashboard system is essential. It should allow a more synthetic and relevant visualization of the design project.

8 Conclusion

Taking into account the requirements as well as providing a benchmark for the performance evaluation of the design activity is a vital asset to the design project managers today. In thischapter, we synthesized the existing tools and models seen in the literature and gaps corresponding to the particular situation of the design activity. Then We present the model CodeSteer and specifications of a software implementation of the model that take into account the duality composed of a quality benchmark and performance assessment for the design activity. In addition to the technical development of the software application, the current development of this work resides mainly in the definition of a dynamic model for deploying in-situ a global repository in an industrial setting, to provide project managers a tool and a complete and adaptive methodolgy in regard of the design functions and conditions encountered.

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Performance Evaluation of Parallel Manipulators for Milling Application

A. Pashkevich, A. Klimchik, S. Briot, and D. Chablat

Abstract This chapter focuses on the performance evaluation of the parallel manipulators for milling of composite materials. For this application the most significant performance measurements, which denote the ability of the manipulator for the machining are defined. In this case, optimal synthesis task is solved as a multicriterion optimization problem with respect to the geometric, kinematic, kinetostatic, elastostostatic, dynamic properties. It is shown that stiffness is an important performance factor. Previous models operate with links approximation and calculate stiffness matrix in the neighborhood of initial point. This is a reason why a new way for stiffness matrix calculation is proposed. This method is illustrated in a concrete industrial problem.

Keywords Performance evaluation · Kinetostatic modeling · Elastic errors · Parallel manipulators · Milling application

1 Introduction

Currently, parallel manipulators have become more and more popular for a variety of technological processes, including high-speed precision machining [1, 2]. This growing attention is inspired by their essential advantages over serial manipulators, which have already reached the dynamic performance limits. In contrast, parallel manipulators are claimed to offer better accuracy, lower mass/inertia properties, and higher structural rigidity (i.e. stiffness-to-mass ratio) [3].

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These features are induced by their specific kinematic structure, which resists to the error accumulation in kinematic chains and allows convenient actuators location close to the manipulator base. This makes them attractive for innovative robotic systems, but practical utilization of the potential benefits requires development of efficient stiffness analysis techniques, which satisfy the computational speed and accuracy requirements of relevant design procedures.

Generally, the stiffness analysis evaluates the effect of the applied external torques and forces on the compliant displacements of the end-effector. Numerically, this property is defined through the "stiffness matrix", which gives the relation between the translational/rotational displacement and the static forces/torques causing this transition [4]. Similar to other manipulator properties (kinematical, for instance), the stiffness essentially depends on the force/torque direction and on the manipulator configuration [5].

Several approaches exist for the computation of the stiffness matrix, such as the Finite Element Analysis (FEA), the matrix structural analysis (MSA), and the virtual joint method (VJM). Each of methods has their own assumptions and in general approximate/linearized the stiffness model with adequate accuracy for the specific problem. Let us consider the recent modification of the VJM proposed by the authors [6]. It allows extending it to the over-constrained manipulators and applying it at any workspace point, including the singular ones. The method is based on a multidimensional lumped-parameter model that replaces the link flexibility by localized 6-dof virtual springs that describe both the linear/rotational deflections and the coupling between them. The spring stiffness parameters are evaluated using FEA modelling to take into account real shape of the manipulator components. This gives almost the same accuracy as FEA but with essentially lower computational effort because it eliminates re-meshing through the workspace.

In contrast to previous works, the novelty of this chapter appears in the computation of the stiffness matrix for the loaded mode in the neighborhood of static equilibrium with true dimensions links.

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This chapter focuses on the performance evaluation of the milling process for the composite materials via enhancing the precise stiffness model for the compliance errors estimation. VJM is used for the stiffness modeling. It incorporates accurate stiffness properties of links via improved FEA-based stiffness calculation algorithm. This leads to adequate estimation of deflections and allows improving accuracy of manufacturing via accurate planning of the technological process.

The reminder of the paper is organized as follows. In the Sect. 2, it is defined the set of problems which are considered in the paper. Section 3 presents performance evaluation factors. Section 4 proposes a new method for the stiffness modeling of parallel manipulator. Section 5 illustrate the efficiency of the propose technique on the Orthoglide manipulator by specializing it for milling of bathroom component. And, finally, Sect. 6 summarizes the main contributions of the paper.

2 Problem Statement

The main problem to be solved in this article is the accuracy evaluation during the manufacturing step for specific parallel manipulators and technological process. Position accuracy and performances characteristics for the industrial manipulators depend on the technological process, kinetostatic and geometry properties of both manipulator and workpiece. Therefore specializing of the manipulator for the current manufacturing process with respect to the required performances properties allows increasing the position accuracy of the tool.

Mechanical stiffness is one of the most important properties, which have influence on the position accuracy of low mass parallel mechanisms. As it is mentioned in [7] Cartesian stiffness is a nonlinear function of the external loading and depends on the configuration of the manipulator and, as result, of the position of end effector in the workspace [8]. The computed Cartesian stiffness both depends on the stiffness of the links and stiffness model accuracy.

So the aim of this article is to specialize a parallel manipulator for the milling of products made of composite material with known geometric sizes. The idea is to improve the accuracy for the high-speed milling via mass reduction and improving of the stiffness model.

3 Performance Evaluation

Let us present here the most essential technology-oriented performance measures that are used in the design process of a machine-tool. They may be classified into two groups:

- *the measures based on geometric, kinematic and kinetostatic properties*; these measures are based on simple models that evaluate the geometric, kinematic and kinetostatic properties of a mechanism. Their specificity is that they only use the primary geometric parameters of the mechanism, i.e., the size of the base, the length of links, etc.
- *the measures based on dynamic, elastostatic and elastodynamic properties*; these measures mostly use more complicated models. Their specificity is that they not only use the primary geometric parameters of the mechanism, but also the secondary geometric parameters, as for example, the cross-section of links.

Let us now describe them.

3.1 Geometric, Kinematic and Kinetostatic Performances

The most commonly used geometric, kinematic and kinetostatic performances are:

- the velocity transmission factors;
  For appreciating the speed capability of a manipulator, several kinematic performance indices are defined using the Jacobian matrix $\mathbf{J}$ (see [9]), such as the condition number, the largest/smallest singular value (also called the maximal/minimal transmission factor and denoted as $k_v^{\max}$ and $k_v^{\min}$, respectively – Fig. 1a, the dexterity, the manipulability, etc. However, as mentioned by Merlet in [9], the previously cited indices does not take into account the "technological reality" of the mechanism, as they are based on the use of the Euclidian norm of the input velocity vector $\dot{\mathbf{\Phi}}$ ($\|\dot{\mathbf{\Phi}}\|$ being considered equal to 1) while it is clear that each actuator may have a velocity $\dot{\phi}_i \in [-\dot{\phi}_i^{\max}, \dot{\phi}_i^{\max}]$, where $\dot{\phi}_i$ and $\dot{\phi}_i^{\max}$ are the actual and maximal velocities for the actuator i ($i = 1$ to n). Thus, it is necessary to redefine the transmission factors.
  Two types of transmission factors may be used: (i) the velocity transmission factors along all directions of the workspace; in such a case, the unit square is mapped into a parallelepiped (Fig. 1b) and (ii) the velocity transmission along some particular directions of the workspace; in such a case, the unit square is mapped into a hexagon (Fig. 1c) [10].
- the accuracy transmission factors;
  The accuracy of a mechanism may be due to different factors. However, as pointed out by Merlet [11], active-joint errors are the most significant source of errors in a properly designed, manufactured, and calibrated parallel robot. The classical approach consists in considering the

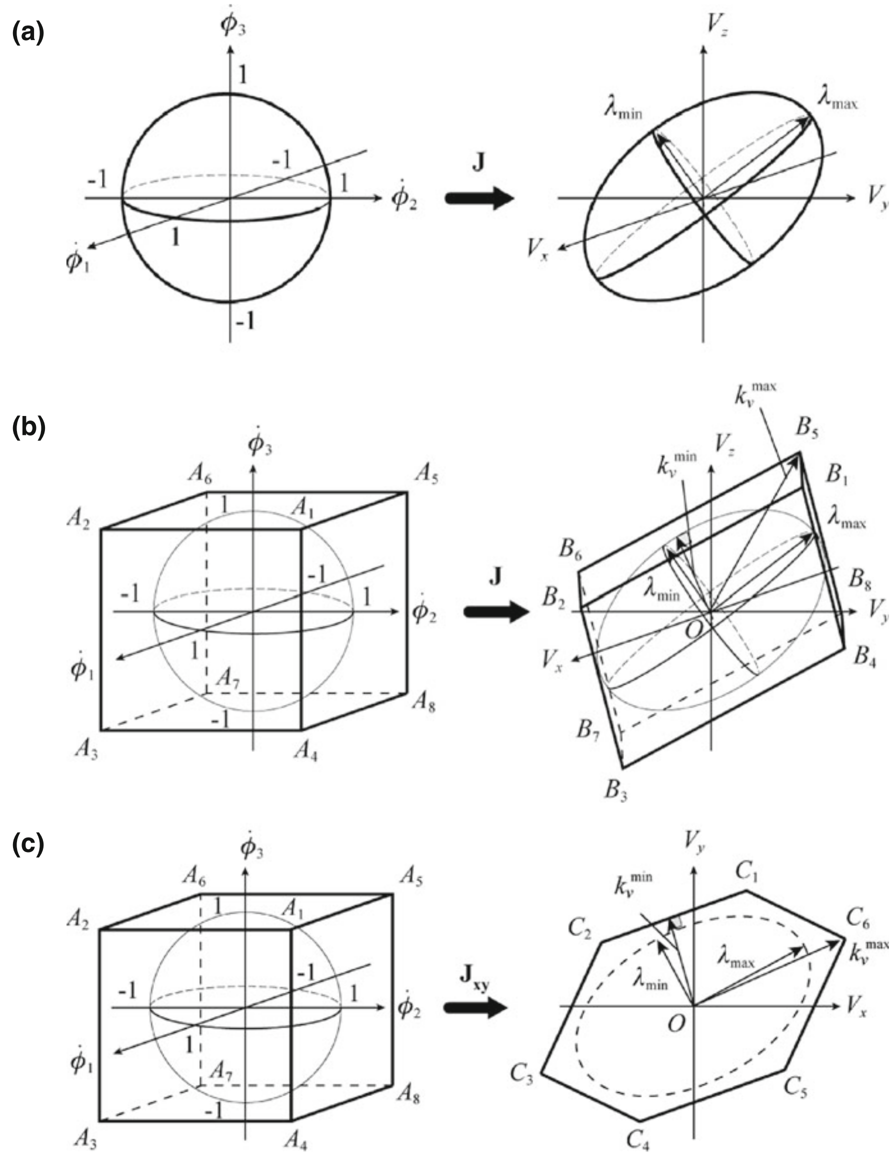

Fig. 1 Mapping, using the Jacobian matrix. (**a**) Mapping of the unit sphere. (**b**) Mapping of the unit cube. (**c**) Mapping of the velocity transmission in the *xy* plane

first order approximation that maps the input error to the output error:

$$\delta \mathbf{p} = \mathbf{J}\,\delta \boldsymbol{\Phi} \tag{1}$$

where $\delta\boldsymbol{\Phi}$ represents the vector of the active-joint errors, $\delta\mathbf{p}$ the vector of end-effector errors. This method will give only an approximation of the end-effector maximum error, but at an optimisation stage, this model may be sufficient.

- It is possible to show that, due the use of the expression (1) as the accuracy model, the accuracy transmission factors are similar to the velocity transmission factors. More information about the computation of these transmission factors is proposed in [9].
- the force transmission factors;

For 3-DOF translational parallel manipulators, the input efforts τ are related to the forces **f** applied on the platform by the following relation:

$$\mathbf{f} = \mathbf{J}^{-T}\,\boldsymbol{\tau} \tag{2}$$

Looking at expression (2), it appears that the relationship for the accuracy is similar to the relationship for the velocity, but $\mathbf{J}^{-T}$ is used instead to $\mathbf{J}$. Moreover, it is also clear that the effort τ_i of one actuator is comprised between $-\tau^{\max}$ and $+\tau^{\max}$, $\tau^{\max}$ being the maximal effort admissible by the actuated pair. So, the force transmission factors may be computed in the same manner as the velocity transmission factors. The maximal and minimal force and moment transmission factors will be denoted as $k_f^{\min}$and $k_f^{\max}$ respectively. To have more information about the computation of these transmission factors, the reader is proposed to refer to [9].

- the size of the workspace;
  Using the set of geometric parameters, the workspace $\mathbf{W}$ may be generated using the kinematic equations and the (passive and active) joint limits [3]. Since, for the considered application, the desired regular workspace is a parallelepiped $\mathbf{W_0}$ of size $\{a_0 \times b_0 \times c_0\}$, the relevant measure may be defined by the largest similar object $\mathbf{W}^{\mathrm{abc}} = \{\mu a_0 \times \mu b_0 \times \mu c_0\}$ inscribed in $\mathbf{W}$, i.e.

$$\mathbf{W}^{\mathrm{abc}} = \mathbf{T}(\mu\,\mathbf{W_0}); \quad (\mu, \mathbf{T}) = \arg\max_{\mu,\mathbf{T}} \{\mu \mid \mathbf{T}(\mu\,\mathbf{W_0}) \subset \mathbf{W}\} \quad (3)$$

  where μ, $\mathbf{T}$ are respectively the scalar scaling factor and the coordinate transformation operator in the Cartesian space. An algorithm that is able to compute the size largest parallelepiped inside a given workspace is presented in [9].

Let us now introduce the dynamic, elastostatic and elastodynamic performances.

3.2 Dynamic, Elastostatic and Elastodynamic Performance

The most commonly used dynamic, elastostatic and elastodynamic performances are:

- the total mass of the robot;
  This is probably the simplest performance measure. The masses of the different elements of a robot have a direct influence on its dynamic behaviour. For one given structure with fixed value of links length, the robot that will have the smallest mass will be the one with the smallest input efforts, and as a result, the highest acceleration capacity.
- the input efforts;
  The input efforts, denoted as τ, depend on the mass and axial moment of inertia of links, such as friction in joints and position, velocity and acceleration of the robot. There expression is given by:

$$\boldsymbol{\tau} = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) + \mathbf{J}^T\mathbf{f} \quad (4)$$

  where $\mathbf{M}$ is the mass matrix, $\mathbf{C}$ the matrix of the Coriolis, centrifugal and viscous friction effects, $\mathbf{G}$ is the matrix of the gravity and Coulomb friction effects. $\mathbf{q}$, $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$ represent the vectors of the positions, velocities and accelerations of the actuators. $\mathbf{f}$ is an external force applied on the platform. Generally, it is considered that, given a desired trajectory, the robot that has the lowest input efforts along the trajectory has the best performance.
- the maximal deformations;
  For parallel manipulators, elasticity is an essential performance measure since it is directly related to the positioning accuracy and the payload capability. Mathematically, this benchmark is defined by the stiffness matrix $\mathbf{K}$, which describes the relation between the linear/angular displacements $\delta\mathbf{t}$ of the end-effector and the external forces/torques $\mathbf{f}$ applied on the tool:

$$\mathbf{f} = \mathbf{K}\,\delta\mathbf{t} \quad (5)$$

It is obvious that elasticity is highly dependent upon geometry, materials and link shapes that are completely defined with the CAD model. The stiffness matrix may be computed using three methods: the finite element analysis (FEA) [12, 13], the matrix structural analysis (SMA) [14, 15] and the virtual joint method (VJM) [6, 16, 17].

Whatever will be the way to compute the deformations of the robot, the mechanism that will have the best elastostatic performances will be the one that will have the smallest deformations under a given force, along a specific trajectory or in the totality (or some portions) of the workspace.

External forces are caused by the coupling of the tool and machining piece. But previous stiffness models calculate stiffness matrix in the neighborhood of initial point and operate with links approximations. Such models can't guarantee good accuracy. Therefore let us consider the stiffness model improvement and deflections evaluation.

4 Stiffness Model

4.1 Problem of Stiffness Modeling

To evaluate the manipulator stiffness, let us apply the VJM method that assumes that the traditional rigid model is extended by adding virtual joints, which describe stiffness of the actuator and links. Thus, the end-effector position for each chain of the manipulator can be described as

$$\mathbf{t} = \mathbf{g}(\mathbf{q}, \boldsymbol{\theta}) \quad (6)$$

where $\mathbf{g}(...)$ is the geometry function which depends on the passive $\mathbf{q}$ and virtual joint $\boldsymbol{\theta}$ coordinates, the vectors $\mathbf{q} = (q_1,\ q_2,\ ...,\ q_n)^T$ includes all passive joint coordinates, the vector $\boldsymbol{\theta} = (\theta_1,\ \theta_2,\ ...,\ \theta_m)^T$ collects all virtual joint coordinates, n is the number of passive joins, m is the number of virtual joints.

This expression includes both traditional geometric variables (passive and active joint coordinates) and stiffness variables (virtual joint coordinates).

To evaluate the manipulator ability to respond to external forces and torques, it is necessary to introduce additional equations that define the virtual joint reactions to the corresponding spring deformations. For analytical convenience, corresponding expressions may be collected in a single matrix equation

$$\boldsymbol{\tau}_{\boldsymbol{\theta}} = \mathbf{K}_{\boldsymbol{\theta}} \cdot \boldsymbol{\theta} \tag{7}$$

where $\boldsymbol{\tau}_\theta = \left(\tau_{\theta,1},\ \tau_{\theta,2},\ ...,\ \tau_{\theta,m}\right)^T$ is the aggregated vector of the virtual joint reactions, $\mathbf{K}_{\boldsymbol{\theta}} = diag\left(\mathbf{K}_{\theta,\mathbf{1}},\ \mathbf{K}_{\theta,\mathbf{2}},\ ...,\ \mathbf{K}_{\theta,\mathbf{m}}\right)$ is the aggregated spring stiffness matrix of the size $m \times m$, and $\mathbf{K}_{\theta,i}$ is the spring stiffness matrix of the corresponding link.

For the compliant link, the matrix $\mathbf{K}$ can be computed using the FEA-based techniques, which usually produce rather accurate result. Using the FEA, the stiffness matrix $\mathbf{K}$ (or its inverse $\mathbf{k}$) is evaluated from several numerical experiments, each of which produces the vectors of linear and angular deflections $(\mathbf{t},\boldsymbol{\varphi})$ corresponding to the applied force and torque $(\mathbf{F},\mathbf{M})$. Then, the desired matrix is computed from the linear system

$$\mathbf{k} = \begin{bmatrix} \mathbf{F}_1 & ... & \mathbf{F}_m \\ \mathbf{M}_1 & ... & \mathbf{M}_m \end{bmatrix}^+ \cdot \begin{bmatrix} \mathbf{t}_1 & ... & \mathbf{t}_m \\ \boldsymbol{\varphi}_1 & ... & \boldsymbol{\varphi}_m \end{bmatrix} \tag{8}$$

where $[\ ]^+$ is pseudoinverse of the rectangle matrix, m is the number of experiments ($m \geq 6$) and the matrix pseudoinverse is replaced by the inverse in the case of $m = 6$. It is obvious that this case with special arrangement of the forces and torques is numerically attractive (for more detail see [18]).

In order to increase accuracy it is worth to improve the deflection estimation technique. It is proposed to evaluate $(\mathbf{t},\boldsymbol{\varphi})$ from the *displacement field* describing transitions of rather large number of nodes located in the neighborhood of reference point (RP).

To formulate this problem strictly, let us denote the displacement field by a set of vector couples $\{\mathbf{p}_i,\ \Delta\mathbf{p}_i | i = 1, 2, ..., n\}$ where the first component $\mathbf{p}_i$ define the node initial location (before applying the force/torque), $\Delta\mathbf{p}_i$ refers to the node displacement due to the applied force/torque, and n is the number of considered nodes. Then, assuming that all the nodes are close enough to the reference point, this set can be approximated by a "rigid transformation"

$$\mathbf{p}_i + \Delta\mathbf{p}_i = \mathbf{R}(\boldsymbol{\varphi}) \cdot \mathbf{p}_i + \mathbf{t}, \quad i = 1, 2, \ldots, n \tag{9}$$

that includes as the parameters the linear displacement $\mathbf{t}$ and the orthogonal 3×3 matrix $\mathbf{R}$ that depends on the rotational displacement $\boldsymbol{\varphi}$. Then, the problem of the deflection estimation can be presented as the best fit of the considered vector field by Eq. (4) with respect to six scalar variables incorporated in $\mathbf{t}$, $\mathbf{R}$.

In general case, the desired stiffness model is defined by a non-liner relation

$$\mathbf{F} = \boldsymbol{\xi}(\boldsymbol{\Delta}\mathbf{t}) \tag{10}$$

that describes resistance of a mechanism to deformations $\boldsymbol{\Delta}\mathbf{t}$ caused by an external force/torque $\mathbf{F}$ [1]. It should be noted that the mapping $\boldsymbol{\Delta}\mathbf{t}\rightarrow\mathbf{F}$ is strictly mathematically defined and physically tractable in all cases, including under-constrained kinematics and singular configurations of the manipulator. However, the converse is not true.

In engineering practice, function $\boldsymbol{\xi}(...)$is usually linearized in the neighborhood of the static equilibrium $(\mathbf{q},\ \boldsymbol{\theta})$ corresponding to the end-effector position $\mathbf{t}$ and external loading $\mathbf{F}$. For the unloaded mode, i.e. when $\mathbf{F} = \mathbf{0}$ and $\boldsymbol{\theta}_\mathbf{0} = \mathbf{0}$ the stiffness model is expressed by a simple relation

$$\mathbf{F} \approx \mathbf{K}(\mathbf{q}_\mathbf{0},\ \boldsymbol{\theta}_\mathbf{0}) \cdot \boldsymbol{\Delta}\mathbf{t} \tag{11}$$

where $\mathbf{K}$ is 6×6 "stiffness matrix" and the vector $\mathbf{q}_0 = (q_{01},\ q_{02},\ ...,\ q_{0n})^T$ defines the equilibrium configuration corresponding to the end-effector location $\mathbf{t}_0$, in accordance with the manipulator geometry.

However, for the loaded mode, stiffness model have to be defined in the neighborhood of the static equilibrium that corresponds to another manipulator configuration $(\mathbf{q},\ \boldsymbol{\theta})$, which is caused by external forces $\mathbf{F}$. In this case, the stiffness model describes the relation between the increments of the force $\boldsymbol{\delta}\mathbf{F}$ and the position $\boldsymbol{\Delta}\mathbf{t}$

$$\delta\mathbf{F} \approx \mathbf{K}(\mathbf{q},\ \boldsymbol{\theta}) \cdot \delta\mathbf{t} \tag{12}$$

where $\mathbf{q} = \mathbf{q}_\mathbf{0} + \boldsymbol{\Delta}\mathbf{q}$ and $\boldsymbol{\theta} = \boldsymbol{\theta}_\mathbf{0} + \boldsymbol{\Delta\theta}$ denote the new position of the manipulator, $\boldsymbol{\Delta}\mathbf{q}$ and $\boldsymbol{\Delta\theta}$ are the deviations of the passive joint and virtual spring coordinates.

Hence, the problem of the stiffness modeling in the loaded mode may be divided into two sequential subtasks: (i) stiffness model identification from the vector field of displacements and (ii) linearization of relevant force/position relations in the neighborhood of the loaded configuration. Let us consider these two sub-problems consequently.

4.2 Stiffness Model Identification

To estimate the desired deflections $(\mathbf{t},\boldsymbol{\varphi})$, let us apply the least square technique that leads to minimization of the sum of squared residuals

$$f = \sum_{i=1}^{n} \left\| \mathbf{p}_i + \Delta\mathbf{p}_i - \mathbf{R}(\boldsymbol{\varphi})\,\mathbf{p}_i - \mathbf{t} \right\|^2 \rightarrow \min_{\mathbf{R},\mathbf{t}} \tag{13}$$

with respect to the vector $\mathbf{t}$ and the orthogonal matrix $\mathbf{R}$ representing the rotational deflections $\boldsymbol{\varphi}$ The specificity of this problem (that does not allow direct application of the standard methods) are the orthogonally constraint $\mathbf{R}^T\mathbf{R} = \mathbf{I}$ and non-trivial relation between elements of the matrix $\mathbf{R}$ and the vector $\boldsymbol{\varphi}$ To reduce the computational efforts, let us linearize the rotational matrix $\mathbf{R}$ [18]. This allows to rewrite equation of the "rigid transformation" (4) in the form

$$\Delta\mathbf{p}_i = \mathbf{p}_i \times \boldsymbol{\varphi} + \mathbf{t}; \quad i = \overline{1,n} \tag{14}$$

that can be further transformed into a linear system of the following form

$$\begin{bmatrix} \mathbf{I} & \mathbf{P}_i \end{bmatrix} \begin{bmatrix} \mathbf{t} \\ \boldsymbol{\varphi} \end{bmatrix} = \Delta\mathbf{p}_i; \quad i = \overline{1,n} \tag{15}$$

where $\mathbf{P}_i$ is a skew-symmetric matrix corresponding to the vector $\mathbf{p}_i$. Then, applying the standard least-square technique and shifting the origin of the coordinate system to the point $\mathbf{p}_c = n^{-1}\sum_{i=1}^{n}\mathbf{p}_i$ leading to expression

$$\begin{bmatrix} \mathbf{t} \\ \boldsymbol{\varphi} \end{bmatrix} = \begin{bmatrix} n^{-1}\mathbf{I} & \mathbf{0} \\ \mathbf{0} & \left(\sum_{i=1}^{n}\hat{\mathbf{P}}_i^T\hat{\mathbf{P}}_i\right)^{-1} \end{bmatrix} \cdot \begin{bmatrix} \sum_{i=1}^{n}\Delta\mathbf{p}_i \\ \sum_{i=1}^{n}\hat{\mathbf{P}}_i^T\Delta\mathbf{p}_i \end{bmatrix} \tag{16}$$

that requires inversion of the matrix of size 3×3. Here, following the adopted notation $\hat{\mathbf{P}}_i$ is a skew-symmetric matrix corresponding to the vector $\hat{\mathbf{P}}_i = \mathbf{p}_i - \mathbf{p}_c$.

By its general principle, the FEA-modeling is an approximate method that produces some errors caused by the discretization. Beside, even for the perfect modeling, the deflections in the neighborhood of the reference point do not exactly obey the Eq. (4). Hence, it is reasonable to assume that the "rigid transformation" (4) incorporates some random errors

$$\mathbf{p}_i + \Delta\mathbf{p}_i = \mathbf{R}(\boldsymbol{\varphi})\cdot\mathbf{p}_i + \mathbf{t} + \boldsymbol{\varepsilon}_i; \quad i = \overline{1,n} \tag{17}$$

that are supposed to be independent and identically distributed Gaussian random variables with zero-mean and standard deviation σ.

In the frame of this assumption, the expression for the deflections (11) can be rewritten as

$$\mathbf{t} = \mathbf{t}^{o} + n^{-1}\sum_{i=1}^{n}\boldsymbol{\varepsilon}_i; \quad \boldsymbol{\varphi} = \boldsymbol{\varphi}^{o} + \left(\sum_{i=1}^{n}\hat{\mathbf{P}}_i^T\hat{\mathbf{P}}_i\right)^{-1}\sum_{i=1}^{n}\hat{\mathbf{P}}_i^T\boldsymbol{\varepsilon}_i \tag{18}$$

where the superscript "o" corresponds to the "true" parameter value. This justifies usual properties of the adopted point-type estimator (11), which is obviously unbiased and consistent. Furthermore, the variance-covariance matrices for $\mathbf{t}$,$\boldsymbol{\varphi}$ may be expressed as

$$\text{cov}\,[\mathbf{t}] = \frac{\sigma^2}{n}\mathbf{I}; \quad \text{cov}\,[\boldsymbol{\varphi}] = \sigma^2\left(\sum_{i=1}^{n}\hat{\mathbf{P}}_i^T\hat{\mathbf{P}}_i\right)^{-1} \tag{19}$$

allowing to evaluate the estimation accuracy using common confidence interval technique.

Another practical question is related to *detecting zero elements* in the compliance matrix or, in other word, evaluating the statistical significance of the computed values compared to zero. Relevant statistical technique [19] operates with the p-values that may be easily converted in the form $k\,\sigma_a$, where k is usually from 3 to 5 and the subscript "*a*" refers to a particular component of the vectors $\mathbf{t}$,$\boldsymbol{\varphi}$

To evaluate the standard deviation σ describing the random errors $\boldsymbol{\varepsilon}$, one may use the residual-based estimator obtained from the expression

$$\text{E}\left(\sum_{i=1}^{n}\left\|\mathbf{p}_i + \Delta\mathbf{p}_i - \mathbf{R}(\boldsymbol{\varphi})\cdot\mathbf{p}_i - \mathbf{t}\right\|^2\right) = (3n-6)\,\sigma^2 \tag{20}$$

The latter may be easily derived taking into account that, for each experiment, the deflection filed consist of n three-dimensional vectors that are approximated by the model containing 6 scalar parameters. Moreover, to increase accuracy, it is prudent to aggregate the squared residuals for all FEA-experiments and to make relevant estimation using the coefficient $(3\,n-6)\,m\,\sigma^2$, where m is the experiments number.

In addition, to increase accuracy and robustness, it is reasonable to eliminate outliers in the experimental data. They may appear in the FEA-field due to some anomalous causes, such as insufficient meshing of some elements, violation of the boundary conditions in some areas of the mechanical joints, etc. The simplest and reliable method that is adopted in this chapter is based on the "data filtering" with respect to the residuals.

4.3 Stiffness Model in the Loaded Mode

To compute the desired stiffness matrix, let us consider the neighborhood of the loaded configuration and assume that the external force and the end-effector location are incremented by some small values $\delta\mathbf{F}$, $\delta\mathbf{t}$. Besides, let us assume that a new configuration satisfies the equilibrium conditions [7]. Hence, it is necessary to consider simultaneously two equilibriums corresponding to the manipulator state variables $(\mathbf{F}, \mathbf{q}, \boldsymbol{\theta}, \mathbf{t})$ and $(\mathbf{F}+\delta\mathbf{F}, \mathbf{q}+\delta\mathbf{q}, \boldsymbol{\theta}+\delta\boldsymbol{\theta}, \mathbf{t}+\delta\mathbf{t})$. Relevant equations of statics may be written as

$$\mathbf{F}\cdot\mathbf{J}_{\boldsymbol{\theta}}{}^{T} = \mathbf{K}_{\boldsymbol{\theta}}\cdot\boldsymbol{\theta}; \qquad \mathbf{F}\cdot\mathbf{J}_{q}{}^{T} = 0 \tag{21}$$

and

$$\begin{aligned}(\mathbf{F}+\delta\mathbf{F})\cdot(\mathbf{J}_{\boldsymbol{\theta}}+\delta\mathbf{J}_{\boldsymbol{\theta}})^{T} &= \mathbf{K}_{\boldsymbol{\theta}}\cdot(\boldsymbol{\theta}+\delta\boldsymbol{\theta});\\ (\mathbf{F}+\delta\mathbf{F})\cdot\left(\mathbf{J}_{\mathbf{q}}+\delta\mathbf{J}_{\mathbf{q}}\right)^{T} &= 0\end{aligned} \tag{22}$$

where $\delta\mathbf{J}_q(\mathbf{q},\boldsymbol{\theta})$ and $\delta\mathbf{J}_{\boldsymbol{\theta}}(\mathbf{q},\boldsymbol{\theta})$ are the differentials of the Jacobians due to changes in $(\mathbf{q},\ \boldsymbol{\theta})$. Besides, in the neighborhood of $(\mathbf{q},\boldsymbol{\theta})$, the kinematic equation may be also presented in the linearized form:

$$\boldsymbol{\delta}\mathbf{t} = \mathbf{J}_{\boldsymbol{\theta}}(\mathbf{q},\ \boldsymbol{\theta})\cdot\boldsymbol{\delta\theta} + \mathbf{J}_{q}(\mathbf{q},\ \boldsymbol{\theta})\cdot\boldsymbol{\delta}\mathbf{q}, \tag{23}$$

Hence, after neglecting the high-order small terms and expending the differentials via the Hessians of the function $\Psi = \mathbf{g}(\mathbf{q},\boldsymbol{\theta})^{T}\mathbf{F}$, Eq. (22) may be rewritten as

$$\begin{aligned}&\mathbf{J}_{\boldsymbol{\theta}}{}^{T}(\mathbf{q},\boldsymbol{\theta})\cdot\delta\mathbf{F} + \mathbf{H}^{F}_{\boldsymbol{\theta}q}(\mathbf{q},\boldsymbol{\theta})\cdot\delta\mathbf{q} + \mathbf{H}^{F}_{\boldsymbol{\theta\theta}}(\mathbf{q},\boldsymbol{\theta})\cdot\delta\boldsymbol{\theta} = \mathbf{K}_{\boldsymbol{\theta}}\cdot\delta\boldsymbol{\theta}\\ &\mathbf{J}_{q}{}^{T}(\mathbf{q},\boldsymbol{\theta})\cdot\delta\mathbf{F} + \mathbf{H}^{F}_{qq}(\mathbf{q},\boldsymbol{\theta})\cdot\delta\mathbf{q} + \mathbf{H}^{F}_{q\boldsymbol{\theta}}(\mathbf{q},\boldsymbol{\theta})\cdot\delta\boldsymbol{\theta} = \mathbf{0}\end{aligned} \tag{24}$$

and the general relation for the stiffness matrix in the loaded mode can be presented as

$$\left[\begin{array}{cc}\mathbf{J}_{\boldsymbol{\theta}}\mathbf{k}^{F}_{\boldsymbol{\theta}}\mathbf{J}^{T}_{\boldsymbol{\theta}} & \mathbf{J}_{q}+\mathbf{J}_{\boldsymbol{\theta}}\mathbf{k}^{F}_{\boldsymbol{\theta}}\mathbf{H}^{F}_{\boldsymbol{\theta}q}\\ \mathbf{J}^{T}_{q}+\mathbf{H}^{F}_{q\boldsymbol{\theta}}\mathbf{k}^{F}_{\boldsymbol{\theta}}\mathbf{J}^{T}_{\boldsymbol{\theta}} & \mathbf{H}^{F}_{qq}+\mathbf{H}^{F}_{q\boldsymbol{\theta}}\mathbf{k}^{F}_{\boldsymbol{\theta}}\mathbf{H}^{F}_{\boldsymbol{\theta}q}\end{array}\right]^{-1} = \left[\begin{array}{c|c}\mathbf{K}_{F} & \mathbf{K}_{q}\\ \hline * & *\end{array}\right] \tag{25}$$

Hence, the presented technique allows computing the stiffness matrix in the presence of the external load and to generalize previous results both for serial kinematic chains and for parallel manipulators.

5 Application Example

5.1 Industrial Problem

Let us demonstrate the efficiency of our design approach on a concrete problem coming from the industrial sector of the region of Nantes (France). One of the most important activity areas of this region is the manufacturing of bathroom components (shower cabin, washbasin, bathtub, etc.). Most of parts used during the assembly process are made of thermosetting materials. The main operations achieved on these parts is trimming, i.e. the suppression of the edges of the parts in order to obtain a good surface roughness.

The tools used for milling are specific mills, which are composed of a large number a diamond glued on its surface. Therefore the number of tooth is supposed to be infinite. However, the use of these specific tools allows the simplification of the model for computing the milling forces.

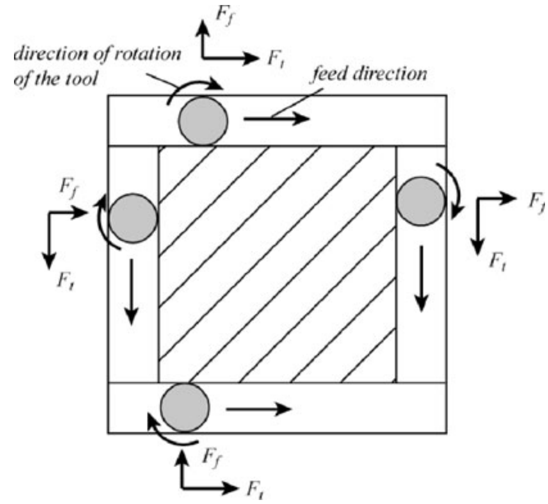

Fig. 2 Trimming operation for composite material

Let us consider the trimming operation depicted at Fig. 2. The milling force may be decomposed into two components, denoted as F_t (the tangential force) and F_f (the radial force) (the vertical component can be neglected for such kind of operation

The machines tools that are used for the trimming of the bathroom components proposed on the Fig. 3 must be designed such as they attain the following characteristics:

workspace $\mathbf{W}^{abc}$ of size {0.5 m × 0.5 m × 0.5 m};
$\|\mathbf{v_{xy}}\| = 60$ m/min ($\mathbf{v_{xy}}$ contains the components of the platform velocity vector $\mathbf{v}$ in the xy plane);
$\|\mathbf{f_{xy}}\| = 300$ N ($\mathbf{f_{xy}}$ contains the components of the external effort vector $\mathbf{f}$ in the xy plane);

Fig. 3 Typical examples of bathroom components manufactured in the region of Nantes (France)

$\|\delta \mathbf{p_{xy}}\| = 0.25\,\text{mm}$ ($\delta \mathbf{p_{xy}}$ contains the components of the platform deformations vector $\delta \mathbf{p}$ in the xy plane).

5.2 Architecture of the Manipulator

For the milling process let us specialize the Orthoglide manipulator (Fig. 4) [20]. This architecture was built in Institut de Recherche en Communications et Cybernetique de Nantes (IRCCyN) and satisfies the following design objectives: cubic Cartesian workspace of size $200\times200\times200\,\text{mm}^3$ (while for selection treatment required workspace $200\times200\times200\ \text{mm}^3$), Cartesian velocity and acceleration in the isotropic point of 1.2 m/s and 14 m/s^2; payload of 4 kg; transmission factor range 0.5–2.0. The legs nominal geometry is defined by the following parameters: $L = 310\,\text{mm}$, $d = 100\,\text{mm}$, $r = 31\,\text{mm}$ where L, d are the parallelogram length and width, and r is the distance between the kinematic parallelogram and the tool centre point. Stiffness model (elements and whole model) of Orthoglide manipulator is presented in [18].

5.3 Performance Evaluation

Since the workspace of the Orthoglide manipulator is lower than required for milling, the length and cross-section of the bar element was increased. Using proposed technique for the stiffness model identification, the new stiffness matrix for the bar element was obtained (Table 1).

Now let us compute the displacements caused by the forces during milling of the composite material. The three subtasks are considered: estimation of the force size, estimation of the displacement through the whole workspace and analyzing of the force direction.

5.3.1 Force Direction Analysis

Here let us plot errors for the constant force (300 N) rotating it from –180 to 180 deg for four typical work points: original configuration ($x = y = z = 0$), two opposite corners of workspace $x = y = z = -200$ and $x = y = z = 300$ and point for nonsymmetrical configuration of the manipulator ($x = -200$, $y = 300$, $z = 0$). Results are presented on Fig. 5. Figure 5a–d show the size of deflections for each direction of the force and represent it in polar coordinates, while Fig. 5e–h show ellipses of deflections in the Cartesian coordinates. As we can see the compliance of the manipulator depends on the direction of external force and on the workpoint. Only for the isotropic work point ($x = y = z = 0$) it is constant for each direction. The lowest and the highest compliant directions of the manipulator differ on $\pi/2$. For the work point $x = y = z = -200$, the manipulator is 7 times stronger in the direction 135/–45 deg than in the direction 45/–135 deg. The maximum compliance is 20% higher than for the single force (Fx, Fy) along the principal directions x

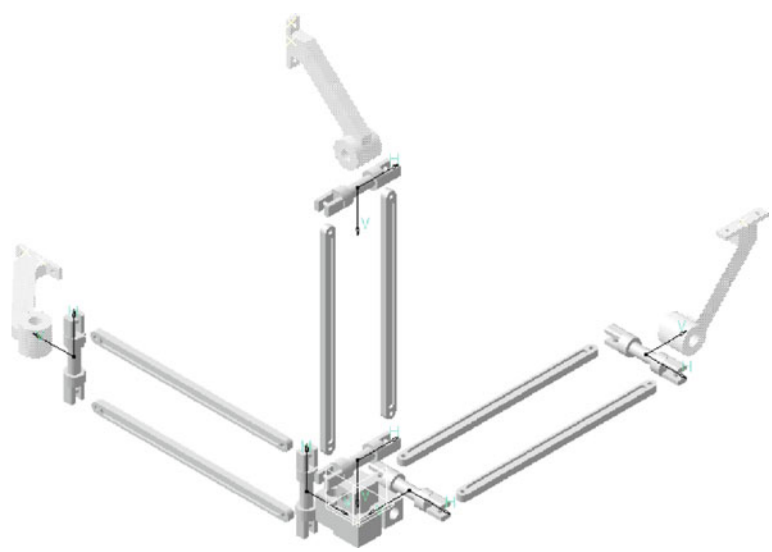

Fig. 4 CAD model of Orthoglide manipulator

Table 1 Stiffness of bar element

	Compliance matrix elements					
Model	k_{11} mm/N	k_{22} mm/N	k_{33} mm/N	k_{44} rad/N.mm	k_{55} rad/N.mm	k_{66} rad/N.mm
Original bar [18]	4.55×10^{-5}	2.33×10^{-1}	5.08×10^{-2}	2.88×10^{-5}	1.50×10^{-6}	7.19×10^{-6}
Revised bar	3.10×10^{-5}	3.54×10^{-1}	6.91×10^{-2}	0.39×10^{-5}	0.33×10^{-6}	1.74×10^{-6}

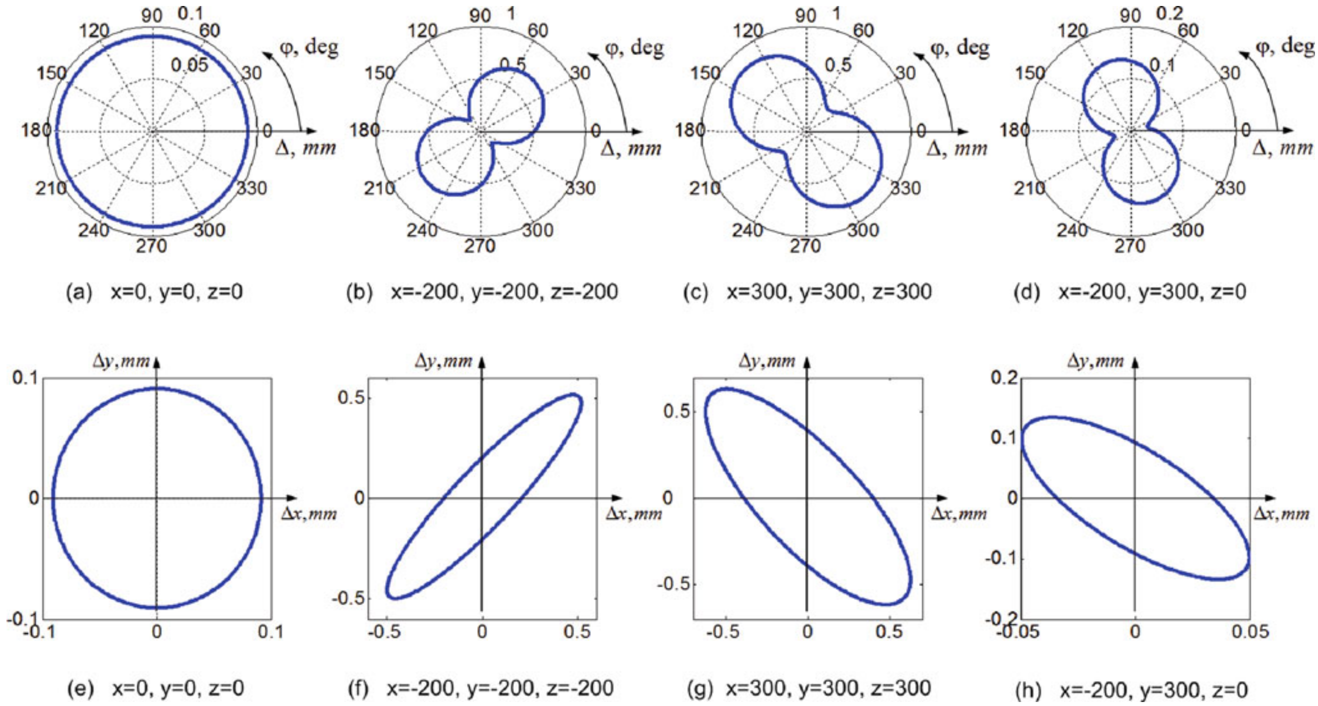

Fig. 5 Norm of the deformations of the end-effector as a function of the direction φ phi of the planar force F=300 N: (**a**)–(**d**) in the polar coordinates $F = (\Delta = \sqrt{\Delta x^2 + \Delta y^2})$; (**e**)–(**h**) in the Cartesian coordinates

and y of the frame. For the work point $x = y = z = 300$, a force oriented along the principal axes of the frame causes deformations 20% less than for the worst direction and 50% more than for the strongest direction. It should be noted that in the workpoint ($x = -200$, $y = 300$, $z = 0$), forces along x and y directions cause different deformations. Along the x direction, the deformations are close to the minimum, while along the y direction, they are close to the maximum. The rate between the maximal and minimal deformations is about 7.

5.3.2 Force Size Analyses

Results for the same four workpoints are presented on Fig. 6. The force-deflection relationship for the force less than 1000 N is linear, but depends on the manipulator configuration. Another conclusion is that in the work point $x = y = z = 0$, the required accuracy can be satisfied for the force up to 600 N, while for all other tested workpoints, it can be satisfied only for forces inferior to 100 N. Moreover, taking into account the force direction, maximum compliance errors for the force 300 N may raise up to 1 mm and more

5.3.3 Workspace Analysis

For the accuracy control through the whole workspace, error maps for opposite planes ($z = -200$ mm Fig. 7a and $z = 300$ mm Fig. 7c) and for the "zero plane" ($z = 0$ mm Fig. 7b) of workspace are presented. It should be noted that the position accuracy depends on the configuration of the manipulator and vary from 0,1 mm to more than 0.5 mm for $z = -200$ and $z = 300$. The accuracy of the "zero plane" is satisfied for the operation, while for $z = -200$ mm, guaranteed

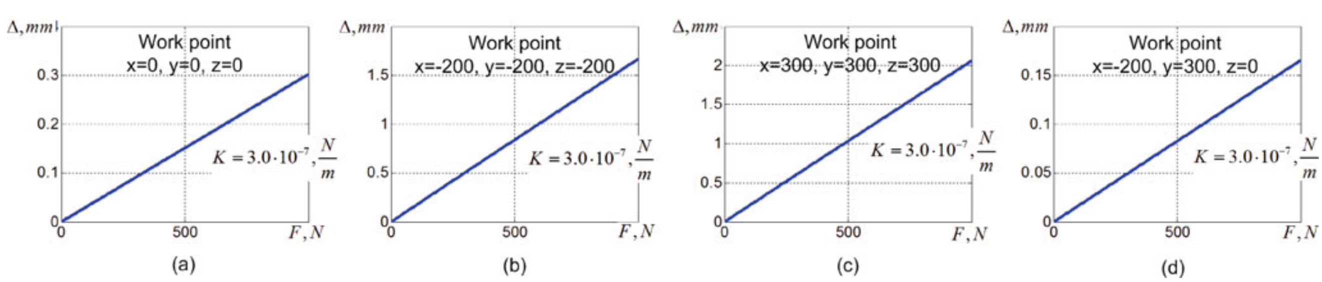

Fig. 6 Force-deflections relationship in the four test points

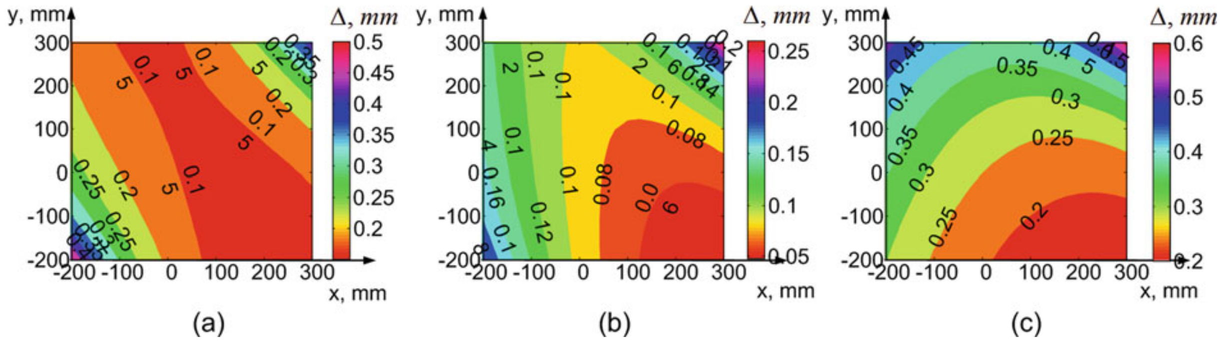

Fig. 7 Error maps for the revised manipulator

accuracy is only 0.4 mm, and for $z = 300$, 0.5 mm. But milling in the strongest direction of the manipulator leads to an accuracy more than 0,2 mm. So, optimizing the milling process for the specialized Orthoglide manipulator may improve the accuracy more than 3 times.

6 Summary

The accuracy of milling of composite materials depends on the number of factors such as accurate kinematic and stiffness modeling, performance evaluation, force control, planning of milling process and others. This chapter contributes to the methodology, which is used for the accurate stiffness modeling for the manipulator and it links for the estimation of the deflections errors. It allows evaluating compliance errors caused by the technological process and detecting strongest and lowest directions for the compliance errors. Using this information for the planning of the milling process allows increasing the accuracy of processing of the pieces made of composite materials.

The method is efficiently illustrated on the milling of bathroom components produced in the Nantes region. For the manufacturing, Orthoglide manipulator was revised, and deformations for different forces and work points were presented. The results allow estimating the accuracy of technological process and improving it by the accurate planning of the milling.

While analyzing the modeling results, the several directions for prospective research activities were identified. They include accurate modeling of milling, improving stiffness of the manipulator for the working direction and compliance deformation compensation in the milling process.

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Priority Evaluation of Product Metrics for Sustainable Manufacturing

A. Gupta, R. Vangari, A.D. Jayal, and I.S. Jawahir

Abstract This chapter presents a framework to develop comprehensive product metrics for sustainable manufacturing and perform a priority evaluation of the metrics. Recent efforts made in this direction produced a large number of influencing factors and metrics for sustainable manufacturing. It is difficult to evaluate the sustainability content of a product with a large set of metrics and there is a need to prioritize these as per the requirements of different industrial segments. The use of analytic hierarchy process to prioritize the influencing factors for electronic products is illustrated through a case study. The development of product ontology is urged as a prerequisite to the ultimate solution for product manufacturers.

Keywords Product life-cycle · Sustainable manufacturing · Product metrics · Analytic hierarchy process · Ontology

1 Introduction

Product design and manufacture in the current scenario requires a great integration of life-cycle data, sustainable product/process designs and their implementation in the manufacture of innovative engineered products. Sustainable products are generally defined as those products providing environmental, societal and economical benefits while protecting public health, welfare and environment over their full commercial cycle, from the extraction of raw-materials to final disposition [1]. The old concept of "from cradle to grave" is now transforming into "from cradle to cradle" [2], and this is a very powerful and growing force for change in the manufacturing industry. According to the National Council for Advanced Manufacturing (NACFAM) in the U.S. sustainable manufacturing includes the manufacturing of sustainable products, and the sustainable manufacturing of all products [3].

Research performed in the area of product sustainability has produced various indicators, influencing factors and metrics. However, there is a lack of application of science-based methodologies to evaluate the quantitative content of such indicators. Also, it is difficult to evaluate the sustainability content of a product with a large set of indicators and there is a need to prioritize these as per the requirements of different industrial segments.

This chapter presents a case study to prioritize the influencing factors for product sustainability using analytic hierarchy process (AHP). The influencing factors considered are based on the previous work done at the University of Kentucky. The priority evaluation of influencing factors will help in decision making while evaluating choices for making the product more sustainable. Further, an attempt has been made to develop the metrics for product sustainability on the basis of these influencing factors. The influencing factors give a measure of broad and subjective impact, but the metrics are defined to mathematically determine the impact more precisely. Development of a comprehensive set of sustainability metrics for products is a necessary step towards developing any product sustainability evaluation. These metrics can also be prioritized further using AHP calculations based on the needs of different industrial segments.

An important aspect in developing these indicators and metrics is the consideration of the triple bottom line for sustainability (environment, economy and society) and all four stages of the product life-cycle (pre-manufacturing, manufacturing, use and post-use). There is significant emphasis on the environmental aspect of sustainability in the current literature. For example, the International Organization for Standardization (ISO) has developed several standards for environmental management under the ISO 14000 family [4]. This includes Environmental Management Systems

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(ISO 14001), Life-cycle Assessment (ISO 14040), and Environmental Performance Measurement (ISO 14031). These standards provide a generic framework for the various commercials tools available to evaluate the environmental impacts of products. However, as mentioned above, true sustainability assessment should comprehensively include societal as well as economic aspects in addition to environmental impacts. This chapter presents a framework to develop comprehensive product metrics for sustainable manufacturing, as well as a method to evaluate priority of the metrics for simplified assessment and decision making. The indicators and metrics presented in this work are classified according to the three aspects of sustainability and the four product life-cycle stages.

2 Total Life-Cycle Considerations in Product Design for Sustainability

Categorizing the developed indicators and metrics into the four life-cycle stages of a product makes the design process comprehensive and identifies some key metrics that would have been missed otherwise. The four key stages of a manufactured product in a closed loop system are represented as: pre-manufacturing, manufacturing, use, and post-use [5].

Pre-manufacturing: The foremost stage in the life-cycle of any product is the extraction of raw material from the natural reserves. Pre-manufacturing includes mining metal ores and smelting them into metal alloys, extraction of crude oil and processing it into hydrocarbons, cutting trees and transforming them into usable wood or paper, etc.

Manufacturing: It is the phase where raw materials are transformed into finished products. A wide range of processing techniques is involved in this phase based on the desirable performance characteristics needed to be incorporated into the final product. Assembly (manual or automated), product packaging and advertising are also considered to be a part of the manufacturing phase.

Use: The use phase pertains primarily to the amount of time the consumer owns and operates the product. During its use stage, the product needs to be energy-efficient, safe, reliable, easy to operate, maintain and repair, etc.

Post-use: The post-use stage involves the final processing of a product for disposal, incineration, recycling, remanufacturing, or other end-of-life processing. Different end-of-life options can be considered during this stage to prolong the product life-cycle and also to ensure perpetual material flow.

This brief explanation helps in understanding the significance and gamut of different life-cycle stages. The indicators and metrics should be grouped into these stages only after a reasonable understanding of the scope of each one of them.

3 Previous Work on Product Sustainability Evaluation

Amongst the earlier attempts made at product sustainability measurement, Fiksel et al. [6] developed some product sustainability indicators and categorized these under environmental, societal and economic aspects. Dickinson and Caudill [7] developed the sustainability target method (STM), which links the economic value of a system with its environmental impact by defining the relative indicator resource productivity for environmental impact and the absolute indicator eco-efficiency for sustainability. Kaebernick et al. [8] and Ritzen and Beskow [9] developed procedures that consider environmental effects at the design stage of product development. Ungureanu et al. [10] developed a sustainability scoring method for manufactured automotive products by considering six elements of sustainability. In industry, one of the most significant attempts made in the direction of sustainability indices comes from Ford in the automotive sector. Schmidt and Butt [11] developed a product sustainability index (PSI), which is implemented as a sustainability management tool in the Ford product development system. PSI includes environmental (global warming potential, air quality, sustainable materials, restricted substances), social (mobility, safety), and economic (ownership cost) aspects of sustainability [12]. Amongst all these efforts, it can be observed that the emphasis has been on assessing the environmental impact. A number of studies are primarily based on ISO 14000 standards series, which is pre-dominantly environmental. This makes it more of an environmental impact assessment, rather than sustainability assessment of the product.

Research activities in the area of product sustainability at the University of Kentucky have focused on considering the economic as well as societal aspects, in addition to the environmental aspect. Early work by Jawahir and Wanigarathne [13] identified six major sustainability elements and numerous sub-elements in manufactured products. The broadly identified sustainability elements are: product's environmental impact; societal impact; functionality; resource utilization and economy; manufacturability; and recyclability/remanufacturability. De Silva et al. [14] developed a comprehensive methodology for the evaluation of product sustainability at the design and development stage of consumer electronic products. The six major "Sustainability elements" identified are shown in Fig. 1. The main elements were further classified into sub-elements and influencing factors.

The influencing factors come from all three aspects of sustainability. Some examples are: environmental factors (toxic substances, emissions, etc.), societal factors (safety,

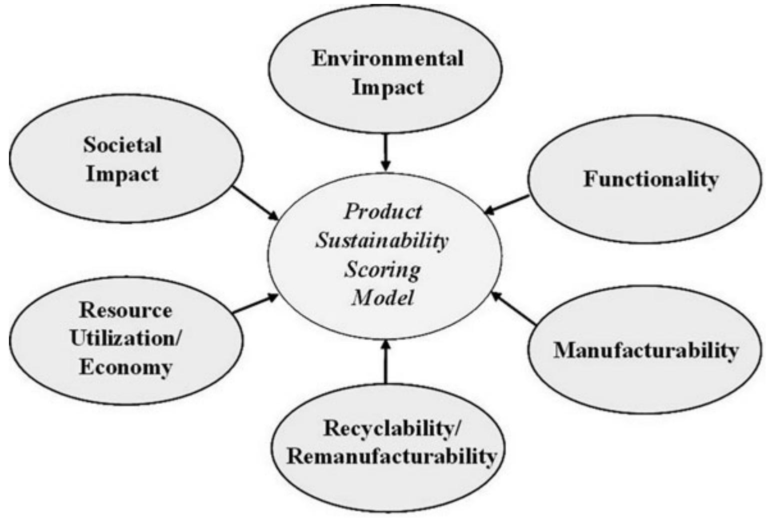

Fig. 1 Six elements of product sustainability [14]

quality of life, etc.), and economic factors (cost of production energy, cost of material, etc.). This makes the methodology holistic in terms of sustainability assessment. A case study was performed on a laser printer manufactured by Lexmark International, Inc. to validate the methodology.

Jawahir et al. [15] evaluated the sustainability content of a product using a product sustainability index (PSI), incorporating the three major components of sustainability (economy, environment and society), over all four life-cycle stages. The calculated index is generic and can be applied to a wide range of products. All the influencing factors considered were categorized into a table, as shown in Fig. 2. The rows in the table represent the three aspects of the triple bottom line of sustainability while the columns represent the four life-cycle stages. The influencing factors are placed in the corresponding rows and columns accordingly. The influencing factors are identified and weighed (out of 10) based on their relative importance and company priorities. Averages for the weighing values were taken across the rows and columns to come up with an overall product sustainability index value.

4 Analytic Hierarchy Process (AHP) and Its Applications

Considerable subjectivity is involved in measuring the influencing factors for product sustainability [14, 15]. These factors need to be quantified using science-based methodologies that can provide more accurate measures of overall sustainability content. In addition to this, the industries always emphasize the need for fewer factors to measure the sustainability content of the products. This can be achieved by performing a priority evaluation of these influencing factors. Analytic hierarchy process (AHP), and its generalization, the analytic network process (ANP), are widely used mathematical techniques that can prioritize a mixed group of elements with both qualitative and quantitative nature, minimizing the subjectivity involved. AHP can be integrated with different techniques, such as linear programming, quality function deployment, fuzzy logic, etc., and this enables the user to make optimal decisions [16].

The application of AHP as a decision making tool is well-known in a wide range of sectors such as banking, industrial engineering, government and political establishments, education, and management [17]. A recent ANSI workshop also emphasized the need to have decision making processes, such as AHP, that can be applied with flexibility based on varying needs for product sustainability standards [18].

Tummala et al. [19] formulated an AHP model to assess the success factors, benefits and costs in order to develop strategies to implement concurrent engineering in Hong Kong electronic products manufacturing companies. Yan et al. [20] used AHP to effectively select partners participating in a collaborative design and bidding process, and this method was subsequently employed for finalizing the product concept and supply chain.

In the area of sustainability, the applications of AHP are mostly restricted to environmental impact. There is an increasing awareness about the environmental impact generated by electronic waste, and this has led the manufacturers to consider Design for Environment (DfE) as a possible option. Li et al. [21] developed a fuzzy graph based modular product design methodology to implement DfE strategies. The fuzzy relationship values were determined by applying AHP

		Influencing Factors in the Product Life-cycle Stages									
		Pre-manufacturing	Score out of 10	Manufacturing	Score out of 10	Use	Score out of 10	Post-use	Score out of 10		
Sustainability Components	Environment	Material Extraction	7	Production Energy Used	7	Emissions	9	Recyclability	7		
		Design for Environment	8	Hazardous Waste Produced	9	Functionality	8	Remanufacturability	8		
		Material Processing	6	Renewable Energy Used	8	Hazardous Waste Generated	9	Redesign	7		
								Landfill Contribution	7	(%) PSI_{en} =	77.29
		(%) $PSI_{(en\_pm)}$ =	70	(%) $PSI_{(en\_m)}$ =	80	(%) $PSI_{(en\_u)}$ =	86.67	(%) $PSI_{(en\_pu)}$ =	72.5		
	Society	Worker Health	8	Work Ethics	7	Product Pricing	7	Take-back Options	7		
		Work Safety	8	Ergonomics	7	Human Safety	9	Re-use	6		
		Ergonomics	7	Work Safety	8	Upgradeablility	7	Recovery	7		
						Complaints	8			(%) PSI_{so} =	73.54
		(%) $PSI_{(so\_pm)}$ =	76.67	(%) $PSI_{(so\_m)}$ =	73.33	(%) $PSI_{(so\_u)}$ =	77.5	(%) $PSI_{(so\_pu)}$ =	66.67		
	Economy	Raw Material Cost	6	Production Cost	6	Maintenance Cost	7	Recycling Cost	7		
		Labor Cost	3	Packaging Cost	7	Repair Cost	6	Disassembly Cost	8		
				Energy Cost	8	Consumer Injury Cost	8	Disposal Cost	4		
				Transportation Cost	5	Consumer Warranty Cost	7	Remanufacturing Cost	7	(%) PSI_{ec} =	61.25
		(%) $PSI_{(ec\_pm)}$ =	45	(%) $PSI_{(ec\_m)}$ =	65	(%) $PSI_{(ec\_pu)}$ =	70	(%) $PSI_{(ec\_pu)}$ =	65		
		(%) PSI_{pm} =	63.89	(%) PSI_{m} =	72.78	(%) PSI_{u} =	78.06	(%) PSI_{pu} =	68.06	(%) PSI_{TLC} =	70.69

Symbol				
Score	Excellent 85-90%	Good 70-84%	Average 50-69%	Poor < 50%

Fig. 2 A framework for a comprehensive total life-cycle evaluation matrix for product sustainability [15]

to life-cycle environmental objectives along with other functional and production concerns. Rao et al. [22] used AHP for evaluating environmentally conscious manufacturing (ECM) programs for producing a given product. Pun et al. [23] developed an AHP-based decision model to assess the determinants of EMS (ISO 14001 environmental management system) adoption in the industry. Kuo et al. [24] constructed a hierarchical structure of environmentally conscious design using AHP, based on five aspects: energy, recycling, toxicity, cost and material. The most desirable design alternative was further selected based on the fuzzy multi-attribute decision-making. Ong et al. [25] incorporated AHP into a pre-LCA software tool to do a comparative environmental scoring for polystyrene and porcelain plates. Singh et al. [26] developed a composite sustainability performance index for steel industry by considering the economic, environmental, societal, organizational governance and technical aspects of sustainability.

The uniqueness of the AHP based case study presented in this chapter is that the developed hierarchy comprises of the three major sustainability aspects and the four life-cycle stages of a product. Further, the influencing factors are placed in the hierarchy after categorizing these under sustainability aspects and life-cycle stages. The hierarchical structure developed based on the conceptual framework is shown in Fig. 3.

4.1 Description of the AHP Model Developed, Analysis and Results

The hierarchy has the main goal at the top level, Level 0, as "Product Sustainability." Level 1 has three sustainability aspects: environmental impact, economic impact and societal impact. Each of the three elements of Level 1 is divided into the four life-cycle stages of the product, at Level 2 in the hierarchy. At level 2, (EnPm, EnMn, EnUs and EnPu) denote environmental aspect of pre-manufacturing, manufacturing, use and post-use stages, respectively. Similar classification has been done for societal (SoPm, SoMn, SoUs and SoPu) and economic (EcPm, EcMn, EcUs and EcPu) aspects. The next level is formed by allocating appropriate influencing factors under relevant categories. This is the Level 3, which has 46 influencing factors assigned based on the previous work done at the University of Kentucky [14]. The final set of influencing factors are obtained by simplifying and logically arranging them under four life-cycle stages

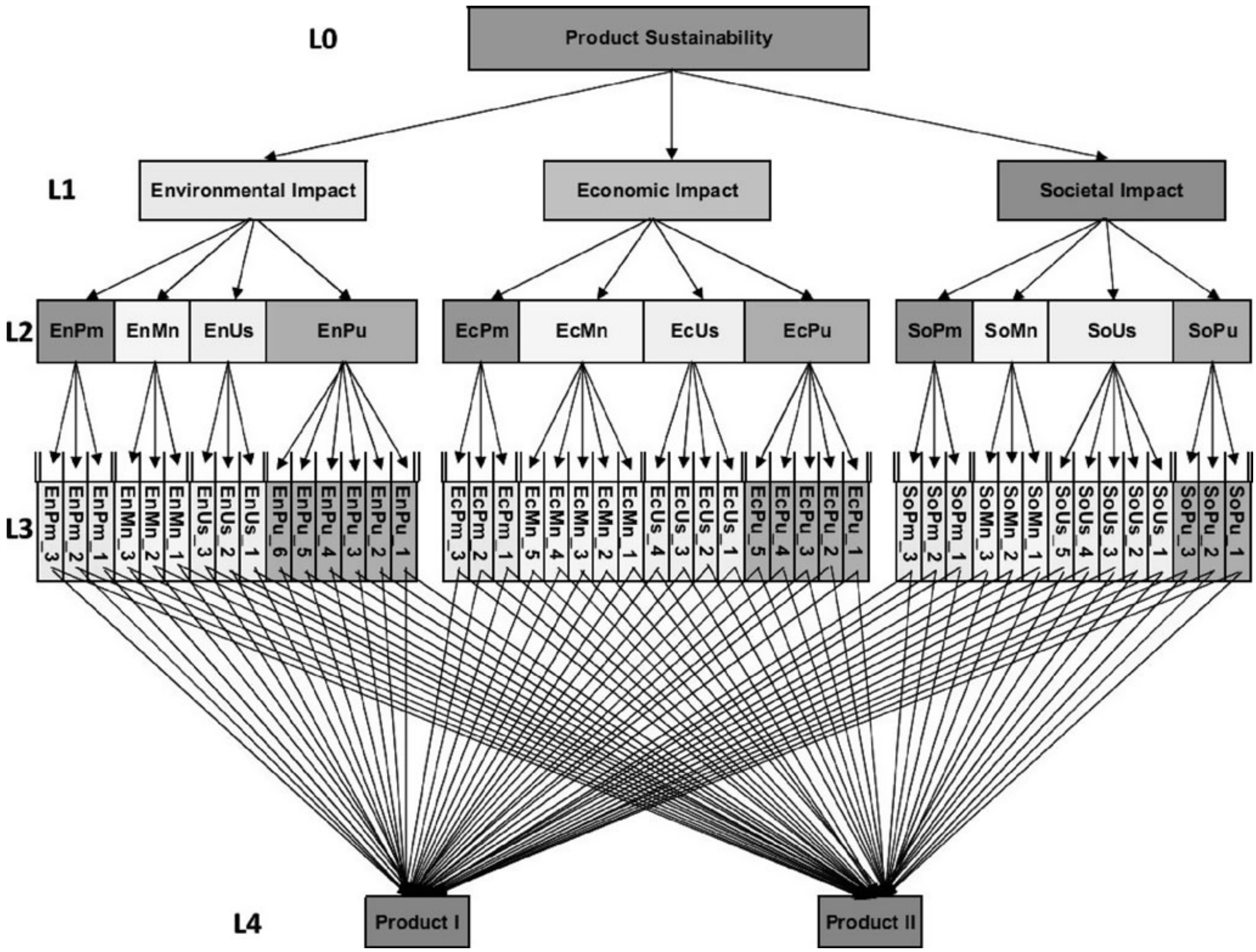

Fig. 3 Product sustainability hierarchy

of the environmental, societal and economic aspects of sustainability. The potential influencing factors are identified based on their importance towards the sustainability of consumer electronic products. An element at Level 3 denoted as (EnPm_2) represents an influencing factor having environmental impact in the pre-manufacturing stage of product life-cycle. These influencing factors are directly connected to the level 4, where two similar products are compared. The products considered are two competitive portable media players (mp3/video players) available in the market, having identical features and technical specifications. A web-based survey was developed for doing the pair-wise comparison of different elements involved. The collected data is analyzed using AHP calculations.

AHP basically involves the pair-wise comparison of different factors under a node and generates a comparison matrix for each node. For example, the pre-manufacturing stage under the environmental aspect consists of three influencing factors, as shown in Fig. 3. The three factors are compared pair-wise and a [3×3] comparison matrix is formed for this node. A node consisting of (n) factors is represented by a [$n \times n$] matrix. These matrices are reciprocal as shown below.

$$\begin{array}{cccc} & A & B & C \\ A & 1 & a_{12} & a_{13} \\ B & 1/a_{12} & 1 & A_{23} \\ C & 1/a_{13} & 1/a_{23} & 1 \end{array}$$

where, A, B, C are the factors to be compared and a_{12}, a_{13}, a_{23} are obtained from the pair-wise comparisons *AB, AC and BC*, respectively.

The priority values of the elements are obtained from the Eigen values of this matrix. The Eigen value method estimates the relative weights and the priority values (local ranking in the matrix) for every set of factors in the hierarchy.

Table 1 Influencing factors, and overall sustainability evaluation, for the two electronic products being compared

Influencing factors	Global priority	Prod I	Prod II
Material extraction	0.029	0.17	0.83
Design for environment	0.083	0.88	0.13
Material processing	0.024	0.75	0.25
Production energy used	0.016	0.83	0.17
Hazardous waste	0.116	0.9	0.1
Renewable energy used	0.026	0.5	0.5
Emissions	0.025	0.5	0.5
Functionality	0.005	0.88	0.13
Hazardous waste	0.032	0.5	0.5
Recyclability	0.043	0.9	0.1
Remanufacturability	0.04	0.88	0.13
Redesign	0.021	0.75	0.25
Landfill contribution	0.036	0.75	0.25
Recovery cost	0.018	0.75	0.25
Potential for next life	0.041	0.5	0.5
Raw material cost	0.057	0.25	0.75
Labor cost	0.023	0.17	0.83
Storage cost	0.011	0.25	0.75
Production cost	0.039	0.5	0.5
Packaging cost	0.014	0.17	0.83
Energy cost	0.035	0.25	0.75
Transport cost	0.007	0.5	0.5
Modularity	0.008	0.75	0.25
Maintenance cost	0.005	0.25	0.75
Repair cost	0.004	0.25	0.75
Consumer injury cost	0.011	0.5	0.5
Consumer warranty cost	0.003	0.75	0.25
Recycling cost	0.006	0.83	0.17
Disassembly cost	0.007	0.75	0.25
Disposal cost	0.003	0.75	0.25
Remanufacturing cost	0.003	0.83	0.17
Recycled material value	0.011	0.75	0.25
Worker health	0.02	0.5	0.5
Worker safety	0.029	0.5	0.5
Ergonomics	0.007	0.5	0.5
Work ethics	0.023	0.75	0.25
Ergonomics	0.012	0.5	0.5
Worker safety	0.04	0.5	0.5
Product pricing	0.003	0.25	0.75
Human safety	0.019	0.5	0.5
Upgradability	0.003	0.5	0.5
Complaints	0.005	0.75	0.25
Quality of life	0.01	0.25	0.75
Take back options	0.009	0.88	0.13
Reuse	0.01	0.25	0.75
Recovery	0.007	0.83	0.17
Total product sustainability index		0.61	0.39

The relative weights, combined with local priority values at individual levels, determine the global priority, as shown in Table 1. Corresponding global priorities of the influencing factors are multiplied with individual product scores to evaluate the total product sustainability index. Final calculations show that product I has a total product sustainability index of 0.61, while product II has a total product sustainability index of 0.39. This means that product I is 56% more sustainable compared to product II. Consideration of a comprehensive set of factors that can influence the product makes the calculated total sustainability index very reliable.

4.2 *Extending the AHP Approach for Multiple Product Alternatives*

The current manufacturing environment is highly customized because of changing customer demands and aspirations. Product manufacturers struggle to balance the product mix while optimizing their profits to remain sustainable in the longer term. Comparing multiple product alternatives in terms of the overall sustainability content can help the manufacturers to balance their product mix, maximize profits, reduce environmental impacts, and fulfil corporate social responsibilities. The case study described here can be extended for multiple product alternatives, as shown in Fig. 4. A hierarchy having five product alternatives at the lowest level is presented. All the product alternatives can be compared with respect to the influencing factors at the preceding level. The overall sustainability content for the five product alternatives can be compared similar to that done for two product alternatives in the case study. This provides a robust framework to the manufacturers in decision making.

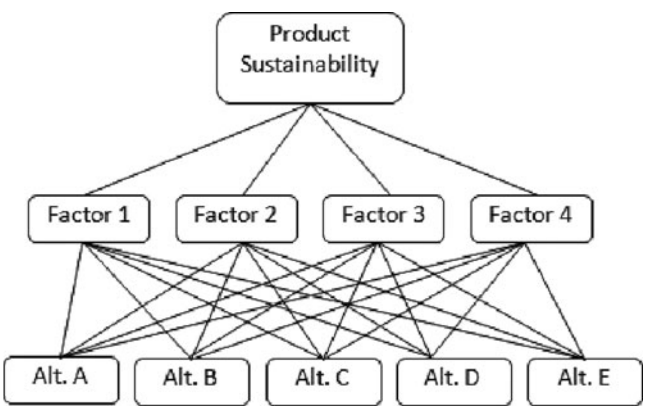

Fig. 4 Product sustainability hierarchy for prioritizing factors from multiple alternatives

5 Proposed Product Metrics for Sustainable Manufacturing

Quantitative evaluation of product sustainability needs product metrics that can be mathematically calculated and precisely measured. A recent OECD [27] study highlights the need for developing suitable indicators and measures for sustainable manufacturing in order to achieve technological and non-technological eco-innovations.

The National Institute for Standards and Technology (NIST) conducted a workshop on sustainable manufacturing, which included a large group of industry-based engineering managers, research and funding agency representatives, software developers and university-based researchers to discuss issues involved in metrics and standards development [28]. NIST has a well-established sustainable manufacturing group actively involved in the development of metrics for sustainable manufacturing.

A large number of industrial segments make it necessary to consider a comprehensive set of influencing factors in the development of product metrics. Therefore, the development of product metrics is a continuously evolving process, and there are issues with the acceptance of any universal product metrics system. Sikdar [29] stated that no consensus exists on a reasonable taxonomy of sustainability related metrics.

According to the American National Standards Institute (ANSI) there is no single approach to standard setting and conformity assessment in the complex area of product sustainability [18]. Another issue with the acceptance of a large set of metrics is the problem in tracking these. Industries continuously emphasize the need for a limited number of metrics that can be easily measured, tracked, and help to achieve higher sustainability levels in the product design and development process. Successful development of such metrics also requires manufacturing industry to have a comprehensive mechanism to measure all the operational elements of sustainable product design and manufacturing.

The product metrics presented here are developed as systematically as the influencing factors considering the three sustainability aspects and the four life-cycle stages of a product. Science-based methodologies such as AHP can be used to prioritize these metrics as per the requirements of different industry segments. The product metrics presented here as examples are developed on the basis of influencing factors for product sustainability discussed in previous sections. Sample product metrics for the environmental, societal and economic aspects of sustainability are shown in Tables 2, 3 and 4, respectively. The metrics for all three aspects are categorized under four life-cycle stages of a product.

6 Product-Ontology Based on the Developed Metrics

There is an increasing trend towards product development using various software tools. This requires a meaningful representation and exchange of product data semantics across different application domains. An ontology based framework to enable such semantic interoperability has been proposed to be developed in recent times [30]. Ontology is an explicit specification of a shared conceptualization [31].

There is a need for formal definitions of product information and all the enterprise applications in a manufacturing system should be able to process this information. This needs information interoperability, which is defined as: the ability of two or more systems to exchange information

Table 2 Examples of environmental metrics for evaluating product sustainability at various life-cycle stages

Pre-manufacture (PM)	Manufacture (M)	Use (U)	Post-use (PU)
Hazardous waste, emissions and landfill (tons/thousand units)	Hazardous waste, emissions and landfill (tons/thousand units)	Hazardous waste, emissions and landfill (tons/thousand units)	Hazardous waste, emissions and landfill (tons/thousand units)
Renewable energy used (% of total energy (PM))	Renewable energy used (% of total energy (M))	Renewable energy used (% of total energy (U))	Renewable energy used (% of total energy (PU))
Total energy used (PM) (energy consumed/unit)	Total energy used (M) (energy consumed/unit)	Total energy used (U) (energy consumed/unit)	Total energy used (PU) (energy consumed/unit)
Ratio of virgin and recycled materials used (per unit)	Ratio of virgin and recycled materials used (per unit)	Modularity – number of structural modules	Potential for next life (% of reusable or recyclable components)
% of raw materials used that are toxic/hazardous	% of raw materials used that are toxic/hazardous	Maintenance or repair energy/unit	
		Ratio of product failures (units returned/thousand units)	

Table 3 Examples of societal metrics for evaluating product sustainability at various life-cycle stages

Pre-manufacture (PM)	Manufacture (M)	Use (U)	Post-use (PU)
Cost of employee education (% of total cost (PM))	Cost of employee education (% of total cost (M))	Cost of user education on post-use opportunities (% of total cost (U))	Cost of employee education (% of total cost (PU))
	% of customized products (with respect to total products made)	% of products with improper operational guidelines (complaints/thousand unit)	% of products offering take-back option
% of employees involved in hazardous operations	% of employees involved in hazardous operations	% of low income customers satisfied (<30 k per annum USD)	% of employees involved in hazardous operations
Cost of societal awareness programs (% of total cost (PM))	Cost of societal awareness programs (% of total cost (M))	Cost of societal awareness programs (% of total cost (U))	Cost of societal awareness programs (% of total cost (PU))
% of minority and disabled employees in the workforce	% of minority and disabled employees in the workforce	Number of consumers injured per thousand units	% of minority and disabled employees in the workforce
% of employees volunteering for social welfare activities	% of employees volunteering for social welfare activities	% of returning customers	% of employees volunteering for social welfare activities

Table 4 Examples of economic metrics for evaluating product sustainability at various life-cycle stages

Pre-manufacture (PM)	Manufacture (M)	Use (U)	Post-use (PU)
Cost involved in employee education (% of total cost (PM))	Cost involved in employee education (% of total cost (M))	Maintenance/repair cost (% of total cost (M))	Cost involved in employee education (% of total cost (PU))
Cost of material and energy inputs/unit	Cost of material and energy inputs/unit	Product quality (defective parts returned per thousand units)	Cost of determining end-of -life options/unit
	Warehouse expenses (% of total cost (M))	Product complaints (per thousand units)	Product redesign and remanufacturing cost (% of total cost (M) for first-life)
	Cost of product cycle time (per unit)	Consumer warranty cost (% of total cost (M))	Disposal cost (% of total cost (PU))
Transportation cost (% of total cost (PM))	Transportation cost (% of total cost (M))		Transportation cost (% of total cost (PU))
	Number and cost of defects (per thousand units)		Product disassembly cost (per unit)
	Sales of reused/remanufactured products (% of total sales)		Product recovery cost (per unit)

and to use the information that has been exchanged [32]. Semantic interoperability of product information refers to automating the exchange of meaning associated with the data among information resources throughout the product development [30]. Various bodies involved with standardization initiatives, such as International Organization for Standardization (ISO) and International Electro-technical Commission (IEC), help in the problem of managing heterogeneous information by formalizing the knowledge related to products [33].

The development of product metrics described in this chapter is a starting point in the development of product ontology. AHP helps in prioritizing the metrics in the order of their importance but the interdependence between the metrics across life-cycle stages and sustainability aspects is not accounted.

Once the interdependencies are established analytically, all the metrics need to be defined and those definitions have to be adopted and understood by enterprise applications across the manufacturing system. This will lead to the development of product ontology based on the developed product metrics.

7 Incorporating Inter-Dependence Within the Developed Influencing Factors/Metrics System

Considerable inter-dependence is observed while developing the influencing factors or metrics system for product sustainability. An influencing factor or metric under environmental aspect can also influence the societal or economic aspect of sustainability. For example, an economic influencing factor "consumer injury cost" can display inter-dependence with societal factors such as "product complaints" and "take-back options". Similarly, a metric categorized under a product life-cycle stage can have influence in other life-cycle stages also.

Analytic network process (ANP), which is a generalization of AHP, can be used to study this interdependence and interaction of higher-level elements in a hierarchy on lower-level elements. The feedback structure used in this methodology enables to and thus helps in the decision making to attain a desired future [34]. The problem is structured as a network in ANP, rather than a hierarchy. A general ANP network consists of different clusters networked with each other. Figure 5 represents a sample product sustainability network considering three aspects of sustainability (environmental, societal, and economic) and product options as four different clusters. The clusters are marked as C1, C2, C3, and C4. A curved double-arrow represents the interrelationship between the nodes within a cluster. For example, the nodes within environmental sustainability cluster are inter-dependent. The same is true for economic and societal sustainability clusters. A double-arrow between cluster C2 and C3 indicates that the nodes within these two clusters have inter-cluster impact. For example, take-back option is a societal metric, which is directly affected by the environmental metrics: potential for next-life life and recyclability. In the ANP questionnaire, these inter-dependencies are accounted for by pair-wise comparing the "take-back option" metric with respect to the two environmental metrics.

The analytical calculations with ANP become very lengthy and complicated for a comprehensive set of influencing factors that are considered in the case-study discussed in

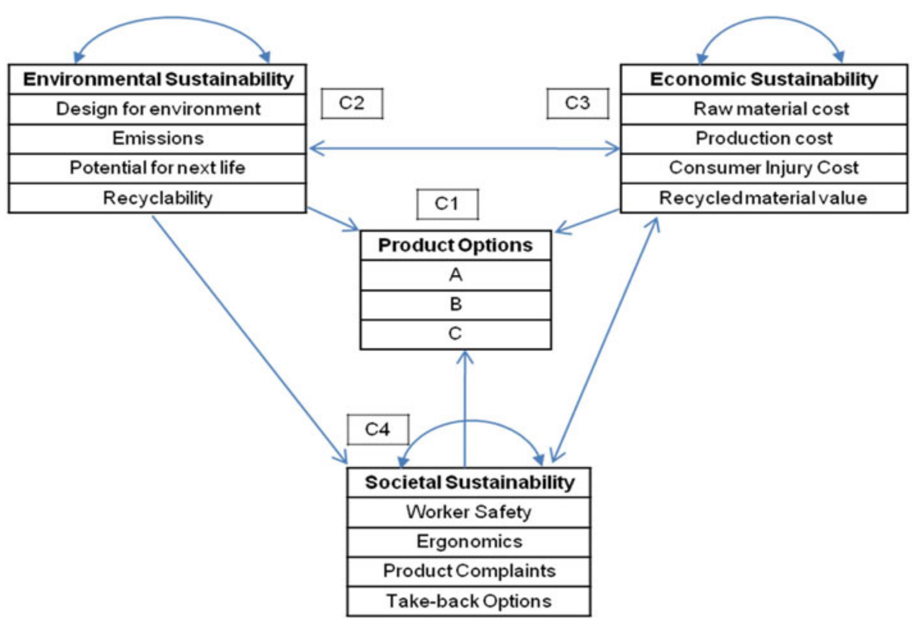

Fig. 5 Proposed sample network for evaluating product sustainability incorporating inter-dependence among influencing factors

this chapter. It needs to start with a smaller network having few clusters and nodes, similar to the one proposed in Fig. 5. After reasonable validation of results obtained with a smaller network, the complete set of influencing factors or metrics can be incorporated to achieve more comprehensive results.

8 Concluding Remarks

This chapter emphasizes the increasing need for developing product metrics for sustainable manufacturing, which can be accepted across a broad range of industrial segments. The importance of quantifying and prioritizing any metric system is presented through a case study on prioritizing inflencing factors for electronic products. The ongoing work at the University of Kentucky includes developing a network based on the product metrics for sustainable manufacturing. To start with, the network will be designed on a small scale taking some of the interdependent metrics into account and building small clusters. The results will be analyzed using the ANP method.

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Using Systems Analysis Techniques to Understand the Relationships Between Skills, Effort and Learning

R.J. Urbanic and W.H. ElMaraghy

Abstract Understanding the associations between skills acquisition, effort and learning is important from many points of view, but these relationships are complex and not well understood. Because these relationships are not well defined, systems analysis tools are used to represent physical and cognitive complexity characteristics, skills coupling and transfer, and learning precedence relationships. These system analysis representations for are to be used as a foundation for a skills-effort-learning framework in order to analyse behaviours for a variety of scenarios.

Keywords Systems analysis tools · Complexity · Learning curve · Skills and knowledge

1 Introduction

Technological developments which require using information from several sources and perspectives, and engaging in activities that require dynamic human-computer interactions, are a way of life today. This can encompass tasks as varied as interacting with a cell phone, a microwave or a design system, programming a 5-axis computer numerical controlled (CNC) machine or performing queries on a Web based search engine. Each system is unique, and must be defined and developed with the end users' functions and abilities in mind. Understanding and balancing the capabilities of the human agents, in conjunction with the development of technical and financial tools, is crucial for long term success. This leads to new engineering challenges: designing systems where the human-machine systems cooperate and support each other over a wide range of scenarios. This extends beyond physical ergonomic tools into cognitive ergonomics, info-ergonomics, Human-Machine [1] or holonic systems. To stay abreast of new consumer demands, designers and developers must constantly engaged in understanding, applying and anticipating new technologies. To this end continuous training is vital; education on new technologies and processes will enable employees to better carry out their tasks and develop a better product. Learning is frequently described as a critical feature of the behaviour of an organization and learning capability is the only source of sustainable competitive advantage [2, 3]. An organization that commits to learning and development at all levels (technical, managerial and manufacturing sectors) and has the ability to adapt to changes is a "learning organization". Yin [2] performed an empirical study relating organizational learning capability to the performance of Computer Integrated Manufacturing (CIM) firms or plants. He concluded that learning capability plays a significant role, and the learning must be aligned properly to generate effective performance.

Another prerequisite is to focus on the identification of the skill sets required to perform tasks at any level of an enterprise, and the development of the appropriate tools to enable employees to operate efficiently across organizational and functional boundaries, either independently or as part of a cross-functional team [4–6]. In manufacturing environments, Kjellberg [7] focuses of the overall process efficiency, and narrows in on the fact that the real bottleneck in organizations is the lack of knowledge. Knowledge improvement strategies should be linked to manufacturing strategies to optimize manufacturing performance. Team learning and competence development is fundamental to this success. Kinnander et al. [8] modelled skill and competence development by applying learning curve theory to specific manufacturing simulations. Two different approaches were evaluated: (1) dedicated operators with limited skills and (2) broad operator competence. The results indicated that the learning phenomenon influences the results and that in an environment that undergoes constant reconfiguration, productivity and costs are directly

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influenced. The results of this simulation verify some of the concepts presented by Kjellberg and Abestam [9].

When considering the overarching view, the physical and cognitive complexity elements of the tasks are interlinked with skills, knowledge and learning acquisition. In addition to this, the nature of the skills and tasks, the learning precedence and the associated coupling of the skills, all impact an individual's learning outcome, as well as the team or organizations. These factors need to be considered systematically and as a whole to understand training and education challenges objectively and to properly align learning objectives with the desired performance. These issues must also be understood when designing systems that require dynamic human-computer interactions. A comprehensive systems approach is presented to understand these relationships, which is the focus of this work. Once a logical model is established that represents skills, tasks, knowledge and learning, a representative framework can be developed, and can be mapped into a mathematical model to analyse behaviours for a variety of scenarios.

2 Learning, Skills, Knowledge and Complexity Overview

In this section, an overview of the learning curve phenomenon, potential skills and training assessment approaches and operational complexity indices, which consider effort levels, are presented.

2.1 Learning Curve and the Power Law of Practice

The time it takes to complete a task decreases with skill acquisition [10, 11]. This is readily observed, and the learning curve phenomenon was first reported in literature approximately 80 years ago. Formal analysis of learning curves first emerged in the mid-1930s. Depending on the type of task, the quality of the results may improve. Therefore, along with the "working time", which is the time required for a task to be completed, the number of operations required and the number of errors can also be used as indices to assess knowledge acquisition. The learning curve phenomenon was first reported in conjunction with manufacturing throughput, and can be simply stated as follows: as the quantity of units manufactured doubles, the number of direct labour hours it takes to produce an individual unit decreases at a uniform rate [11]. The standard learning curve model is:

$$Y = KX^n \tag{1}$$

where Y is the number of direct labour hours required to produce the Xth unit. K is the number of direct labour hours required to produce the first unit. X is the cumulative unit number. $n = \frac{\log \Phi}{\log 2}$, and is the learning index. Φ is the learning rate. $1-_{\Phi}$ is the progress ratio.

Complementing the learning curve is the power law of practice for representing "reinforcement learning". If an operation requires T_1 seconds to perform the first time, then on the nth cycle it will require T_n seconds. This improvement has been experimentally measured, and the empirical model for "practice" is [12]:

$$T_n = T_1 n^{-a} + b \tag{2}$$

where $a = 0.4[0.2 \sim 0.6]$ b is an asymptotic value.

Since the initial description of a log-linear model does not apply to all situations, several alternatives have been proposed, and are illustrated in Fig. 1.

The common models found in the literature are:

- The log-linear model.
- The plateau model.
- The Stanford-Binet model.
- The DeJong model.
- The S-model (i.e., cubic learning curve model).

Yelle [11] concludes that labour intensive operations have a much steeper learning curve slopes (higher progress ratio, as shown in Fig. 2) than capital intensive operations.

A plateau model is much more likely to occur in machine intensive manufacturing. The steady state condition in machine intensive manufacturing systems could be due to unwillingness to set new goals and invest more capital in order to introduce technological improvements necessary to reduce the labour hours.

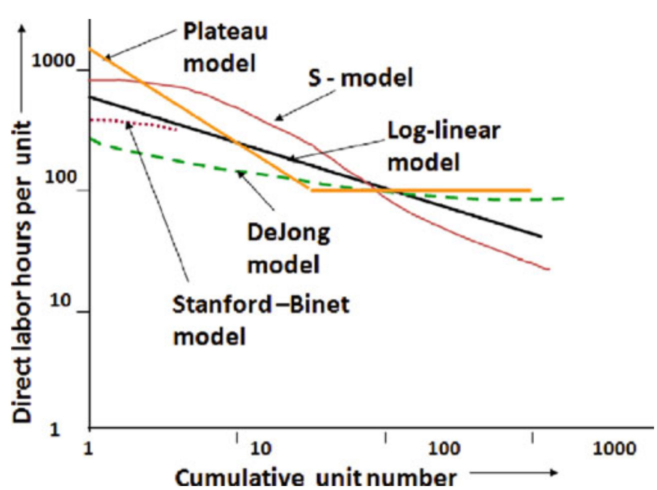

Fig. 1 Learning curve models [11]

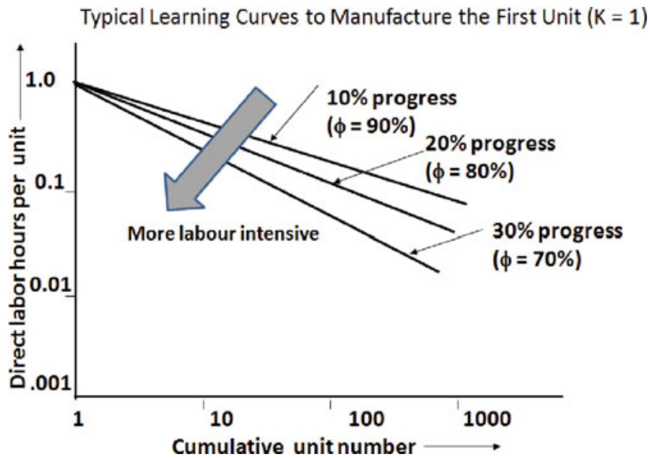

Fig. 2 Learning curve and progress ratio

Most of the early development and applications have been in the area of production engineering; however, the learning curve model is being used in a variety of non-manufacturing scenarios, such as being used to assess a design by monitoring the ease of learning for human–machine interfaces for a global positioning system (GPS) [13] and assessing how beginner-level trainees learn CAD skills in formal training sessions [14]. Badiru and Ijaduola [15] investigate cost and performance models for various learning curve models to measure the resilience of systems. All these researchers consider the learning curve model as a black box model (Fig. 3), where the input is the person and their associated physical and cognitive skill sets, the output is the task being performed at some rate, and the black box consists of the human performance model, which contains physical, cognitive and behaviour elements, and is influenced by the formal knowledge, experiences and abilities of the person as well as the level of difficulty of the task(s) at hand.

2.2 Skills, Rules, and Knowledge

Rasmussen [16] presented a three-tier framework of cognitive processes that distinguishes between skills, rules and knowledge which complements process control tasks (Fig. 4). Routine activities consist of skill based behaviours, which can be conducted quickly and automatically. Skill based behaviours consist of stored, preprogrammed patterns of instructions. "Low level" rigid tasks that require these skills do not require conscious allocation of the actor's attention when performing these tasks. They can be performed automatically or below one's conscious awareness. "Medium level" tasks require conscious attention. The solutions to a situation are governed by rules or heuristics which are learned through training or experience and are associative by nature (if *x* then *y*). There is a longer time element in learning and execution with medium level tasks. In novel situations where there are no pre-established rules or procedures, knowledge based reasoning, which focuses on the state, the goals, and initiates actions to achieve the goals, is required. These "high level" tasks require conscious effort and a plan to be developed to solve a problem and to develop rules. These plans are often required to be changed based on the situation. Consequently, the time element is the longest for knowledge development scenarios.

Initially, one is unskilled or exposed to a novel environment, and requires a high level of attention to perform, whereas a skilled person can perform tasks routinely. The rules, knowledge framework complements training, learning and development concerns for a person or an organization as well as product design concerns related to usage.

One of the goals for designers is to develop an end product (process or system) that is intuitive to use (maintain, service and so forth). Consequently, a quantitative measure that captures skills, rules and knowledge is required, and this needs to be linked to the learning process. Even if employees have all the relevant skills, experience and training, there

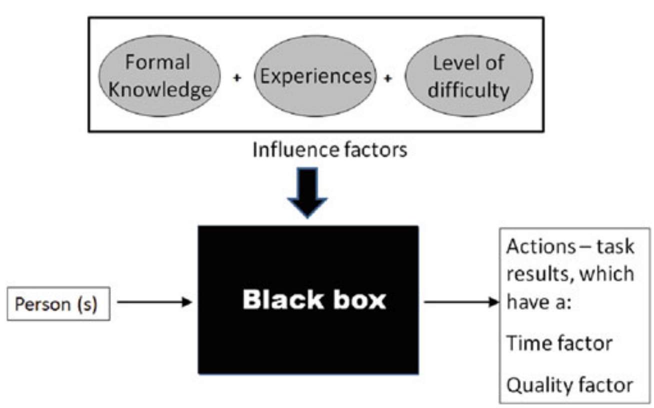

Fig. 3 Learning black box model

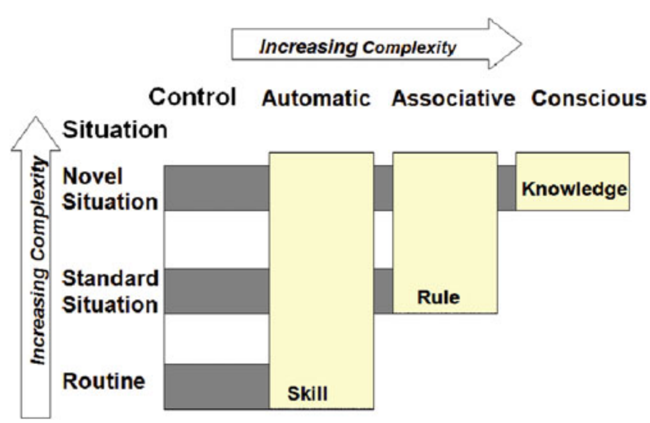

Fig. 4 Skills, rules, and knowledge

is still a learning curve when exposed to a new situation (either product or process). The learning curve characteristics are associated with the complexity of the situation or tasks at hand. The complexity is relative to the novelty of the situation. An adaptable complexity model and metrics is discussed in the next section.

2.3 Complexity Model and Metrics

The general complexity model developed by ElMaraghy and Urbanic [17, 18] is used to assess operational complexity for a skill sets related to manufacturing features using a systematic methodology. The general complexity model consists of a framework that decouples product, process and the operational complexity in the manufacturing domain in order to assess the relative complexity based on criteria relevant to the environment at hand. The number and diversity of features to be manufactured, assembled and tested, and the characteristics of the task sets to be performed (associated with the feature) are assessed systematically. The product, process, physical skill and cognitive aspects as considered and evaluated where appropriate. The operational complexity considers the cognitive and physical effort required to perform the tasks (Fig. 5), and can be extended beyond the manufacturing domain. The operational complexity is transformed by considering the "relative effort" to determine the complexity for a task-feature set.

Skills, effort and complexity are interlinked in the complexity model. For the purposes of this research, effort is considered separately from "complexity". Effort and complexity are related but not equivalent. A complex task may be broken into several simple (effortless) subtasks; consequently, effort can be thought of as a subset of complexity.

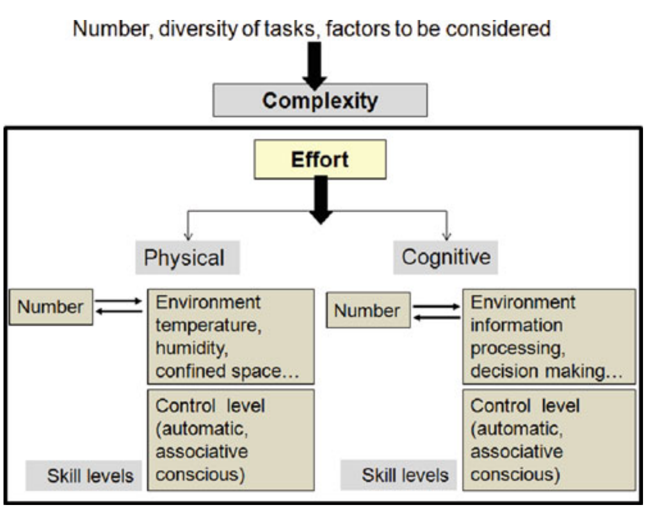

Fig. 5 Complexity, effort and skills

An effortless task is one that is performed routinely, and can be learned quickly.

The effort analysis consists of a framework that allows one to consider physical factors and cognitive factors. Physical factors that could be assessed are: strength, dexterity, coordination and so forth; whereas, the cognitive factors could focus on decision making, and information processing aspects. The operational complexity index *OI* has a product and process element; hence, *OI* varies from 0 to 2. As *OI_product* or *OI_process* $\rightarrow 1$, the complexity increases, and more physical and cognitive effort is required to perform a task.

An example of the operational complexity "relative effort" assessment is illustrated below for a transfer machine used to rough machine a V6 cast iron cylinder block (Fig. 6). The eight main manufacturing feature sets are listed in Table 1, as are the datum features, the number of tools and their descriptions, and well as the head type per station.

The tasks associated with manufacturing these features for this analysis are: changing the tools, and gauging the features with relation and hand gauges, run the machines and making adjustments. The physical and cognitive aspects are listed below. A 0, 0.5 and 1 value is used to rank low, medium and high efforts respectively. The average physical effort and cognitive aspects are calculated for each specific task from an overview perspective, and the average effort is calculated considering both the physical and cognitive elements (Tables 2, 3, and 4).

When plotted, it can be readily seen that the related physical and cognitive effort for these features-machine-tooling-task combination (Fig. 7).

With the higher relative effort index (or complexity index value), the more conscious effort is required as a variety of characteristics are included in the assessment.

The task factors are a function of the task time, cycle time, task quantity, and the number of cycles. Direct or indirect can be considered.

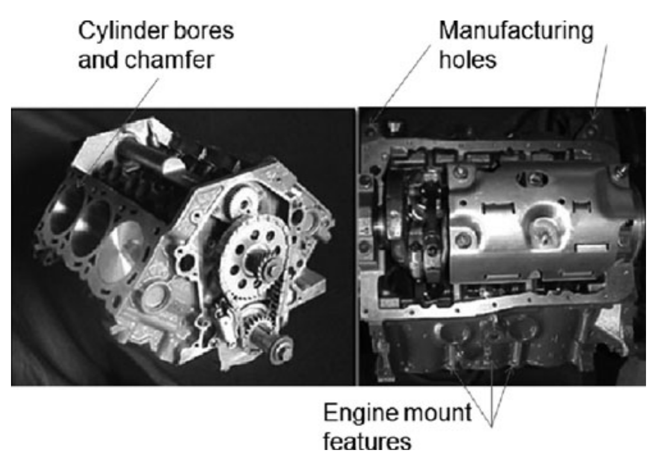

Fig. 6 V6 cast iron cylinder block

Table 1 Manufacturing summary

Features	No. of features	Datum feature, block orientation	Station type	Tool description (per station)	No. of tools	Head description (per station)
Manufacturing holes (datum -B- & -C-)	2	-A- -D- bore split	A	2 drill, 1 bore	3	shuttle head
Locknotchs, bulkheads	4	-A-, -B-, -C-, pan face vert.	B	2 special mill tools	2	turret
Rough cylinder bores	4	-A-, -B-, -C-, pan face down	C	2 multi-insert boring tool	2	shuttle head
Rough cylinder bore chamfer	6	-A-, -B-, -C-, pan face down	C	2 multi-insert feed-out tool (with draw bar)	2	shuttle head
Rough mill front and rear faces	6	-A-, -B-, -C-, pan face down	C	3 milling heads, intricate tool path	3	CNC mill
Mill engine mounts	8	-A-, -B-, -C-, pan face down	C	8 milling heads, intricate tool path	8	shuttle head
Drill engine mounts	8	-A-, -B-, -C-, pan face down	C	8 step drills	8	shuttle head
Drill/ream oil hole	1	-A-, -B-, -C-, pan face down	C	1 step drill, 1 drill, 1 ream	3	orbital head
Sum	39		3 types		31	

Table 2 Physical effort summary

		Physical $J = 5$						
		Physical environment			Physical skills			
Description	Number	Temp	Cleanliness	Envelope	Strength	Dexterity	SUM	Sum/J
Change tools	31	0	0.5	1	0.5	0.5	2	0.40
Gage features[a]	78	0.5	0.5	0.5	0.5	0.5	2	0.40
Run machines[b]	10	0	0	0	0	0	0	0.00
Adjust – mech.	1	0	0	0.5	0	0	0.5	0.10
Adjust – controls[b]	10	0.5	0	0	0	0	0.5	0.10

[a]($\times 2$) due to relation and function gages
[b](1) machine and (9) stations

Table 3 Cognitive effort summary

Physical $K = 3$						
Description	Number	Procedures	In-process relationships	Performance analysis	SUM	Sum/J
Change tools	31	0.5	0.5	0.5	1.5	0.50
Gage features[a]	78	0	0.5	0.5	1	0.33
Run machines[b]	10	0.5	0.5	0.5	1.5	0.50
Adjust – mech.	1	0	0.5	0.5	1	0.33
Adjust – controls[b]	10	0.5	0	1	1.5	0.50

[a]($\times 2$) due to relation and function gages
[b](1) machine and (9) stations

Table 4 Relative effort summary

Task	Task complexity
Change tools	0.45
Gage features	0.37
Run machines	0.25
Adjust – mech.	0.22
Adjust – controls	0.30
Relative effort complexity index	0.32

Direct tasks are steps or work required in the regular course of business (i.e. manual interactive man-machine assembly tasks in a manufacturing line). Indirect tasks consist of ancillary functions such as specialized data collection for process capability assessments, changing tools, adjusting machine settings due to tool wear, and so forth.

There are two general task factors to be considered, as shown below:

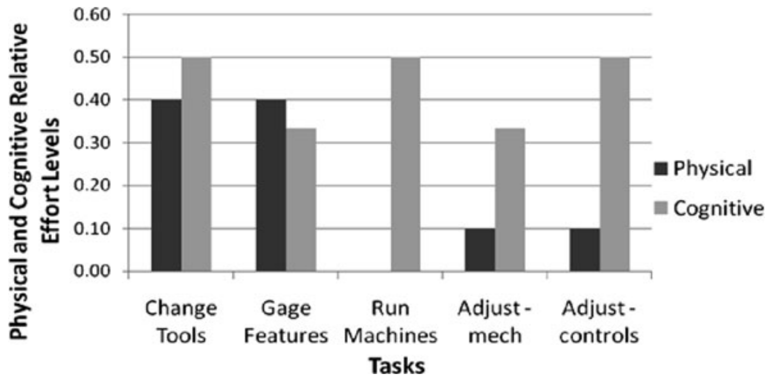

Fig. 7 Relative effort analysis

$$\text{Task Factor}_1 = \frac{\text{Task Time}}{\text{Cycle Time}} \quad (3)$$

$$\text{Task Factor}_2 = \frac{\text{Task Quantity}}{\text{No. of Cycles}} \quad (4)$$

For direct tasks, the task time is usually equal to or less than the cycle time. This is especially true for man-machine interactive tasks such as manual assembly operations. Other direct tasks are performed offline. For example, for high volume production of a cylinder block, the cycle time is in the order of seconds, but gauging a part is in the order of minutes. An associated indirect task is performing tool changes. This may take seconds if working with individual tools on an "as-needed" basis, but may take hours if doing a batch tool change, which is standard for several high volume applications. A comparison of the various production environments using these parameters is shown in Fig. 8.

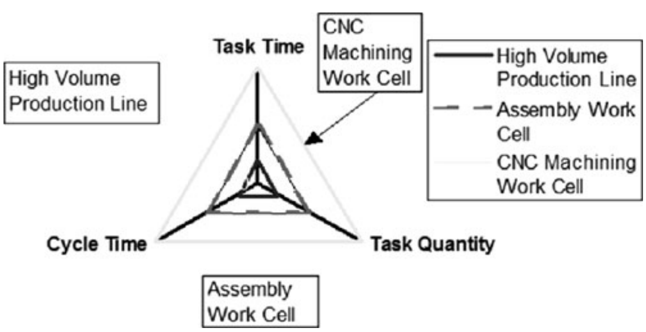

Fig. 8 Cycle time versus task time and quantity for different production environments

The tool change tasks are performed in batch mode for the example, except for the boring tool (summarized in Table 5). There are several similar tool change tasks, as clustered by tool type. The stations were designed with identical features or a family of features (for similarity to balance standardization with fool proofing) where feasible. Skills would be developed faster for changing the drilling tools as compared to the special milling and boring tools. Adjustment of the boring tool is relatively frequent; hence, this skill would be developed relatively quickly and reinforced. However, the controls related adjustments are unique, irregular (> 10,000 cycles), and require information processing and decision making. Hence this task type would require more conscious effort compared to the others with the same effort, as they would be in the associative or repetitive regions (Fig. 9). Levels of previous experience or accumulated knowledge will impact the transition between zones. This is especially true if the machines, tools, gauges and tasks are designed to leverage previous knowledge and experience.

The process of reducing complexity by minimizing effort (breaking tasks into simple physical and cognitive elements), which are similar for different product-tool-machine combinations, is the foundation for dedicated manufacturing systems and the "tall" pyramid organizational structure which

Table 5 Toolchange task factor2 (Eq. (4)) scaled by 100

Tool type group	Number	Adjustable (Y/N)	No. of cycles for tool change/adjustment	Tool change task factor2 ×100
Drill/Reamer	13	N	5000	0.26
Bore	1	Y	300	0.33
Special arbour mill tools	2	N	3500	0.06
Fixed insert rough boring tools	2	N	3500	0.06
Multi-insert feed-out tool (draw bar)	2	N	5000	0.04
Milling cutters	11	N	5000	0.22

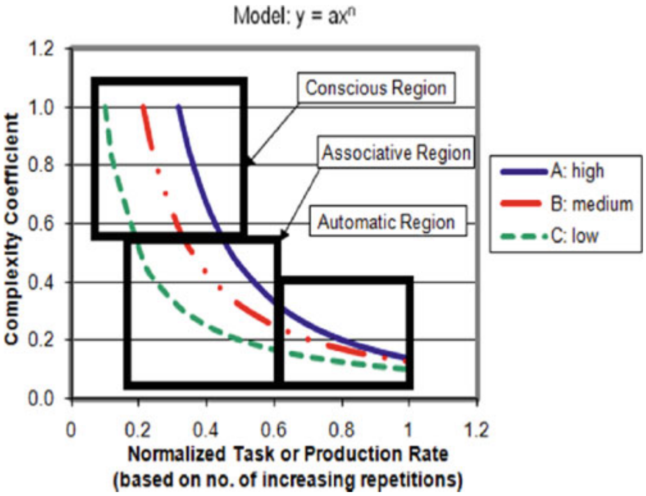

Fig. 9 Complexity, learning and skills trends (the complexity coefficient is related to complexity or effort)

is common for this environment. A general overview analysis is presented here. A more detailed analysis is required to isolate specific issues.

The learning curve assesses the output performance as a whole, and the complexity analysis assesses feature-task pairs on a comparative basis. What is missing from these analyses are relationships such as the learning precedence for the skills, and the associated skills' coupling, as this impact an individual's learning outcome, as well as the team or organizations. This is discussed in the next section.

3 Skills – Tasks Relationships

To consider the skill coupling and relationships, the design structure matrix (DSM) and precedent diagram is used. Certain skill-task sets reinforce others (coupling), or a transfer of skills is necessary (or assumed to be available) in order for one to be effective learning a skill; hence, a precedent relationship exists.

Understanding the skills relationships for "effective" usage of a computer aided manufacturing (CAM) is presented to illustrate these concerns. Here the CAM system is defined to consist of computer aided design (CAD) interface, which links to tool libraries and tool path generation menus, on a workstation (which has an operating system). The resulting program is transferred to a CNC machine after it has gone through a post processing stage. To be able to generate an applicable program, the process planner needs to have an understanding of the following:

1. Workstation operating system (O/S)
2. CAD tools and features
3. CAM tools and features
4. Manufacturing processes and principles
5. Drawing interpretation (blue print reading, geometric dimensioning and tolerances)

These elements can be further expanded upon to include specific design and analysis tools such as tolerance stack ups, multiple manufacturing processes, surface treatments, fixture

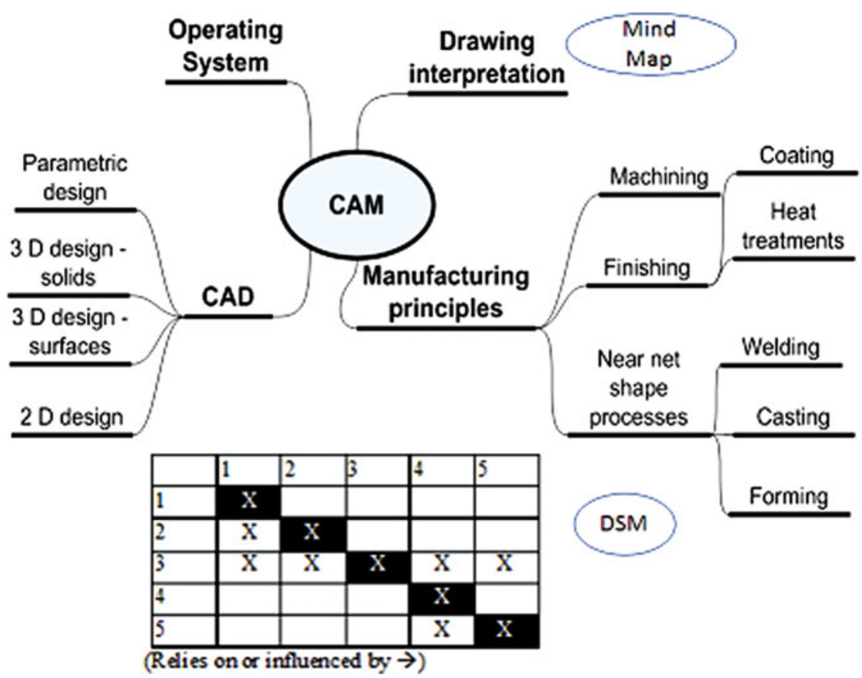

Fig. 10 Basic mind map and design structure matrix for CAM competency

and tooling design, and so forth, but these 5 elements are considered in this example. The mind map and DSM for this is illustrated in Fig. 10.

To be effective using CAD tools on a workstation, one needs to know the operating system at a basic level. For generating tool paths, one needs to know the CAD tools and features, and be able to draw related construction geometry as needed. To select the correct tools and process parameters (i.e., for machining, feeds, speeds, lead in, lead out, step over and so forth), the planner must have some knowledge of manufacturing principles and drawing interpretation. Comprehension of manufacturing principles and drawing interpretation is completely decoupled from understanding an operating system; whereas, an effective demonstration of CAM skills is highly coupled with all listed skills.

The DSM illustrates the coupling, but there is a learning precedence that is not captured with the DSM. To be able to use CAM tools, one should have competency with the operating system (O/S), and CAD tools. This is also true for the drawing interpretation (blue print reading B/P) and understanding of manufacturing principles branch, as shown in Fig. 11.

There can be overlaps in the learning process that are not represented here in this precedence diagram. An alternative format, analogous to a Gantt chart, is presented in Fig. 12 to decompose the learning relationships into another level of granularity, and to illustrate a conceptual learning timeline.

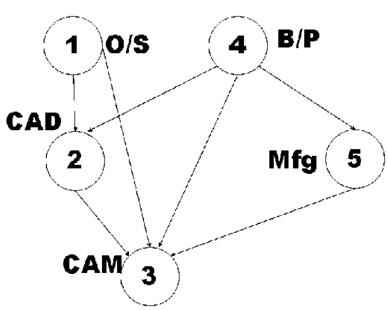

Fig. 11 Basic learning precedence diagram

The basic level indicates a novel situation which requires conscious effort; the functional level is in the associative region, where knowledge rules are established and can be effectively applied; and the expert level indicates the tasks associated with this skill are routine in nature, and the actor is well acquainted with the application. Once a basic level of competency is reached, one may move to the next skill, i.e., one can be learning basic tools without producing functional results. For example, one can learn basic geometry and parametric design tools in either a CAD or CAM system without understanding the manufacturing functional requirements. For practical functional design, there needs to be another level of competency.

This model can also be used to represent knowledge transfer from one specific application to another or to represent specific skills-task combinations. Skill level values can be assigned to represent each region for complexity and effort analyses or vice versa. This precedence representation is visual skills map illustrates both coupling and precedence. Estimating where personnel are along this learning road map can provide insight into the target audience for a new product/process/system, so that the training and documentation can be planned accordingly, either from an employee training or user training perspective.

4 Summary

Understanding the relationships between skills acquisition, effort and learning is important from many points of view. It provides insights for designers engaged in developing new

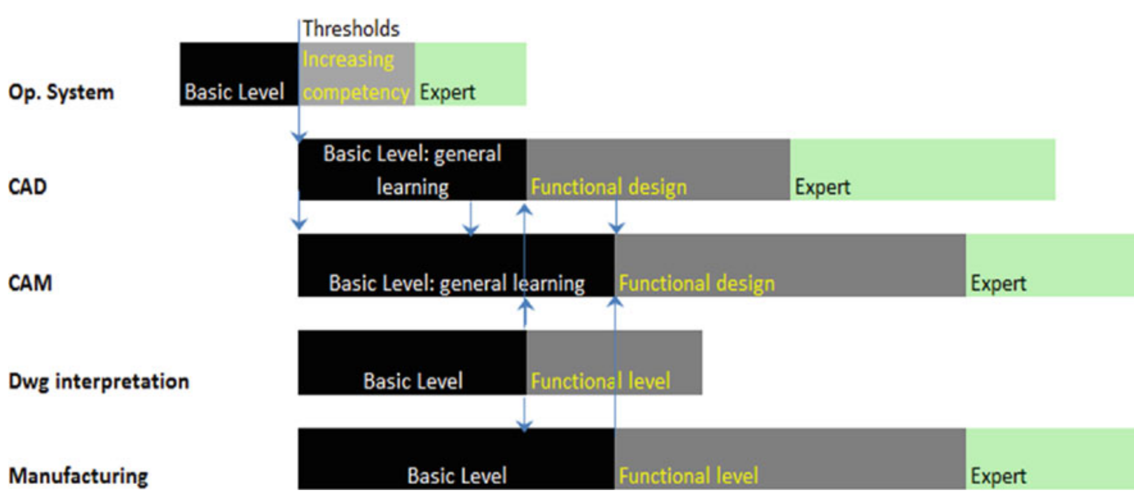

Fig. 12 Expanded precedence diagram indicating competence thresholds and inter-relationships

products and technologies. It is also important for creating effective continuous learning environments, as continuous learning provides individuals and organizations with a competitive advantage. The learning curve is used to analyse progression, but although the learning curve phenomenon is well established, it is a black box model. As recognized by Nakamura et al. [19], the learning curve cannot be directly applied when considering tasks that do not contain a "regular form" or are not consistently repetitive.

Consequently, to comprehend the relationships between the skills, tasks, complexity and learning, system analysis tools are utilized to decompose these relationships. The relationship between skills, rules, and knowledge is presented. Understanding this assists in understanding the complexity associated with various situations and tasks, and a methodology to evaluate physical and cognitive effort characteristics related to tasks is presented.

A modified Gantt chart is utilized to visualize learning precedence, competency thresholds and learning interrelationships. The complexity or "relative effort" of the skills and tasks, the learning precedence and the associated coupling of the skills, all impact an individual's and an organization's learning acquisition, and are represented systematically. These system analysis depictions are to be used as a foundation for a skills-effort-learning framework in order to analyse behaviours for a variety of scenarios.

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Towards a Performance Measurement System for Lean-Oriented NPD Processes

M. Taisch, D. Corti, and S. Terzi

Abstract Lean thinking has been successfully applied to manufacturing and operations environments and many case studies and research papers have extensively been published. The same remark cannot be made for lean application to the New Product Development (NPD) process. Some efforts in Lean Product Development exist, but, until today, with the tools available, it is impossible to say if a NPD process is lean or not, and actually how much lean is. A kind of gap exists in the applicability of lean into the NPD process and this chapter aims at filling this gap, contributing to NPD performance measurement getting a leanness process. The paper proposes a Performance Measurement System, derived from the Balanced Scorecard approach, for measuring a NPD and its leanness. The proposed framework is under development within the LeanPPD European project.

Keywords New product development · Performance measurement system · Lean product development · LeanPPD project

List of Abbreviations

AHP	Analytic Hierarchic Process
BEP	Break Event Point
BS	Balance Scorecard
IPI	Integrated Performance Index
LESAT	Lean Aerospace Initiative
NPD	New Product Development
NPV	Net Present Value
PM	Project Management
PMS	Performance Measurement System
PPD	Product & Process Development
R&D	Research & Development
ROE	Return On Equity
ROI	Return On Investment
SMART	Strategic Management and Reporting Technique
TTM	Time To Market
VSM	Value Stream Mapping
JIT	Just In Time

1 Introduction

In the last years, New Product Development (NPD) process has been increasingly becoming a critical issue, since market competition is leveraging on a multitude of factors, ranging from more and more demanding consumers, to shortened product lifecycles and – above all – Time-To-Market (TTM) compression. In particular, TTM is one of the most critical aspects of NPD. Speeding up NPD permits to have first mover advantages, like increasing the earnings and covering early the costs due to the initial investments. The competition among companies is giving customers the product they want, when they want it, and at the lowest cost, but the main problem is to understand how to shorten and improve the NPD process itself, considering also that being quick often means costs. NPD is a complex process involving many activities, business functions and actors, characterized by cycling flows, with many iterations, high level of creativity and as a consequence high degree of uncertainty. The complexity of a NPD process makes it difficult to be monitored, linearized, and standardized.

A lot of practices and tools are used to get more linear processes. Many of these practices (e.g. Japanese techniques, JIT approach, Concurrent Engineering) are currently grouped under the term "lean". Lean thinking and its principles – as prescribed by Womack and Jones [1] – have been successfully applied to manufacturing and operations environments and many case studies and research papers

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have been published. For the NPD processes the situation is quite different. Although there is an agreement on the definition and characteristics of a "lean product development system" [2] and the lean concepts of enhancing the value and eliminating waste in NPD process have been clearly explained, their quantification has been applied principally to the production flow rather than to the design flow of information.

In the scientific and industrial literature, there is a kind of gap which still exists in the applicability of lean into the NPD process. The present paper aims at filling this gap, contributing to the NPD performance measurement getting a leaner process and aligning it towards the goals of a lean enterprise. The paper proposes a Performance Measurement System (PMS), derived from the well known Balanced Scorecard approach. The objective of such proposal is not only creating a set of indicators but providing a tool that, frequently used, permits to monitor the process, and then understand where acting to improve it. Improving means that a leaner process is obtained and consequently a cheaper product too.

The paper aims at describing in details the developed PMS, and it is structured as follow: Sect. 2 reports the state of the art of PMS for NPD process, Sect. 3 describes the main structure of the proposed PMS, Sect. 4 shows a first application of the PMS within the NPD process of an Italian household appliance manufacturer, while Sect. 5 concludes the paper identifying the next steps of the research and defining the objectives of the European LeanPPD project.

2 Lean and NPD Performance Measurement

This section reports two main axis of state of the art: the first deals with NPD process and its leanness, while the second with the performance measurement of the NPD process.

2.1 Lean Oriented NPD Process

Among the definitions of NPD process, one of the most relevant mentions NPD as "the set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product" [3]. Besides the different existing models of NPD process, according to [4], they can be categorised in to three:

- *Departmental-stage models*: they are the oldest, functional, sequential and "over the wall" ones.
- *Activity-stage models*: they focus on the activities and are the most used.
- *Decision-stage models*: they are characterized by stages (where the activities take place) which are always followed by gates (review points with specific input, exit criteria and go/kill/hold/reiterate decision as output). A recent evolution of the stage-gate vision is the Spiral Development [5], which consists of a series of "Build-Test-Feedback-Revise" iterations.

Within these models, lean approach plays a relevant role for improving the efficiency of NPD. Lean thinking [1] is "the way to do more with less, identifying the value added activities from those that are waste", and its core is constituted by the five following principles:

- *Specify value* in terms of a specific product with specific capabilities offered at a specific price and time.
- *Identify the value stream* for each product within the process.
- *Make the value flow*.
- *Let the customer pull the process*.
- *Pursue perfection continually* by removing successive layers of waste as they are uncovered.

Lean thinking is often seen as a set of tools, like continuous improvement (kaizen), group technology, kanban, takt analysis, poka-yoke, etc. Even if it has origin in the manufacturing world, lean thinking has been applied in other functions or phases, like product launch [6], or in other sectors like services (e.g. healthcare, public sector, hospitality and food, education). With regard to NPD process, different authors (e.g. [2, 7]) tried to apply lean techniques to it. In particular, in 2006 Liker and Morgan [8] suggested that the core of a "lean NPD system" is made by multiple interdependent parts that interact to create a whole and cannot be fully understood by looking at individual parts. These authors identified thirteen principles for a lean NPD, divided into three subsystems: *Process*, *People* and *Tool/Technology*.

Within lean thinking, the starting point for measuring performance is the identification of value and waste. It is difficult to quantify value (and consequently, waste) within the context of NPD, because there are many perspectives on value, waste and on what is valuable. These perspectives depict the complexity of the matter, which is seen differently by customers, final users, shareholders and employees. Methods such as the Value Stream Mapping (VSM) are good tools to map the current state, identify different types of waste and analyse the process flow. Nevertheless, VSM is a qualitative and graphical tool, used for describing and analyzing the process flow to obtain and improve future state, but it does not provide a quantitative definition of the leanness of the NPD process. Global frameworks for transforming a NPD process into a lean one have been developed. The method described by Huthwaite [9] starts with the definition of values (*Ilities*) and waste (*Ings*) in order to solve the Lean Design Equation. LESAT (Lean Aerospace Initiative [10]) is a tool for self-assessing the present state of leanness of an enterprise and its readiness to change. These can be considered roadmap frameworks that translate the change principles into specific guidelines for lean enterprise transformation, defining both the "as is" and the "to be" state. However, they don't include the identification of metrics, which can be useful for providing feedback, pointing out the critical activities and helping the generation of specific improvement solutions over time in order to obtain a lean oriented NPD process. At the present, it is not possible to say if a NPD process is lean or not, and how much lean it is.

2.2 Performance Measurement in NPD

The measurement of performances for planning and control purposes can be traced to the development of the first large companies [11]. Performance Measurement (PM) enables managers and employees to monitor and control resources and actions to achieve predefined targets by taking a process check perspective on the organization. At the operational level, measures for resources (*input*), actions, and process performance (*output*) are monitored and compared with the desired target. Comparison between actual performance and target performance identify gaps (if any) that trigger actions and improvements. The size and direction of the gap (positive or negative) provide information and feedback at the tactical level that can be used to identify efficient process adjustments or other actions. In addition, an appropriate set of measures and timely gap identification by employees support their involvement in the continuous improvement efforts.

Miller [12] argued that PM should facilitate decision making to align actions with strategic objectives and provide feedback on operational performances and internal capabilities to the strategic level. The decision making process involves the selection of appropriate performance measures and targets that will align the behaviour of employees to achieve desired actions and strategic objectives; as a matter of fact, a company achieves its objectives when a performance culture and strategy are reinforced each other [13]. Mintzberg [14] stated that performance control systems can serve two purposes: to measure and to motivate. Zairi and Sinclair [15] in their literature review identified that PM can profoundly affect the motivation of individuals. To carry out effective PM it is imperative to carefully design performance measures at each level in the organization that will support all the above roles. There is a consensus that poorly developed or implemented metrics can lead to frustration, conflict, and confusion [16, 17].

In such a context, *Performance Measurement System* (PMS) is a large research topic, and in the current literature a great variety of frameworks has been developed. Among the plethora of existing PMSs, there are some relevant frameworks, which might be quoted:

- *Strategic Measurement And Reporting Technique* (SMART) [18], which integrates financial and non-financial reporting and links operational measures to strategic goals.
- *Balanced Scorecard* (BS) [19], which shows the different areas of performance that an organisation values most.
- *Performance Prism* [20], a tool used by managers to identify what the key questions are in order to manage their business.
- *Information System approach* [21], based on the consideration that a PMS within an organisation should be considered similar to an information system.

Systematic approaches to performance measures are needed to drive NPD process achieving goals. In doing so, emphasis is on inter-functional effectiveness (overall quality of the product offered) and system flexibility, complemented by a process analysis and cost drivers identification, that help in providing process efficiency and productivity. The crucial role played by product definition effectiveness in the success of a NPD process has been highlighted in [22], who sought to identify the characteristics that separate new product successes from failures. A further refinement of that was suggested by Griffin and Page [23]: they noted that the key to understand an organisation's position regarding NPD is the ability to measure the "success" or "failure" of its development projects, or the extent of success and failure. Effectively managing and measuring NPD process is widely seen as an approach to ensure business survival; existing product development indicators are primarily internal measures that focus on comparing activities and processes to previous operations and targets. Later, the same authors [24] state that the performance indicators used in NPD take principally two forms, financial and non financial one and they developed a set of performance measures for determining the project-level success of product development and the overall success of NPD programs.

Loch and Tapper [25] noted that the outputs of NPD projects are only partially measured if financial measures alone are used. This is because financial measures are too uncertain and too distant in time. Rather, according to these authors, measures need to be operational in nature, and they need to be derived from the company's strategy. Such measures must thus address three types of research outputs: *New technology and breakthrough concepts*, *Customer support* and *Knowledge repository*. Driva [26] considered that a mix of measures is often desirable because it focuses on both the NPD process and the output to permit evaluation of tangible and intangible assets of the organisation. This mix usually comprises hard measures (i.e. quantitative values) and a set of soft measures (techniques such as mail surveys or telephone conversations). A balanced approach to measures permits appropriate attention to internal efficiency and simultaneously encourages creativity, innovativeness and collaborative working during the NPD process. Pillai et al. [27] proposed a model that integrates the key factors of the lifecycle of a NPD project and that indicates its overall performance through an *Integrated Performance Index* (IPI). By adjusting the coefficients of different factors, the IPI was capable of application in the project-selection phase, the project-execution phase, and the implementation phase. The major measures of the overall project lifecycle were defined as customers' delight and goodwill, return on investment, and maximisation of profit. Humphreys et al. [28] proposed a mechanism for evaluating supplier involvement during NPD. The assessment tool included four indices to measure supplier involvement in design: *Satisfaction*, *Flexibility*, *Risk* and *Confidence*. These indices measure the extent to which customer requirements and supplier capabilities match (or fail to match), and thus indicate the potential risk of engaging in a project contract.

According to Chen et al. [29], the NPD PMSs mentioned above are all unable to quantify the level of meeting the customer orientation and objective orientation requirements. Proceeding from the orientation of customer satisfaction, these authors aimed to establish a PMS for NPD based on the concept of "total cost". In their model, "Customer total-cost-based success" is treated as the lead indicator of overall NPD performance. A further refinement in the analysis of NPD literature has been suggested by Swink [30], who stated that NPD characteristics such as project complexity, size, technical content, and product newness increase NPD lead-time.

A set of relevant PMSs for NPD is also available within the literature mainly dedicated to Research and Development (R&D) management and measurement. The level of R&D expenditure has been the most extensively used proxy for the level of innovative effort, since several studies suggested that R&D expenditure, productivity and competitive advantage are positively correlated [31]. Kerssens-van Drongelen and Bilderbeek [32] pointed out that when dealing with companies' R&D objectives and the subsequent measurement of performance in achieving these objectives, it is useful to make a distinction between objectives and performance of the R&D function and those of the R&D organisation. The objective of the R&D function is to successfully initiate, coordinate and accomplish the NPD activities of a company, while the objective of the R&D department is to effectively and efficiently create, sustain and exploit the technological knowledge base needed by the company. Using the BS approach, these authors [32] developed a set of metrics to measure R&D performance from various perspectives, including the financial perspective, the customer's perspective, the innovation-and-learning perspective and the internal business perspective.

Summarising, in literature many PMSs exist, some of them already specifically defined for NPD process measurement. Generally, *Total Cost*, *Product Quality* and TTM are the most common criteria. As [33] observed, these three criteria are the most popular in NPD performance measures, also because of their positive, direct relationship with the same NPD process. The continuous development and market introduction of new products can be an important determinant of company performance. Introducing new products faster than the competition (reduced TTM) allows business opportunities such as setting product standards, being a technical pioneer, being able to rapidly respond to customer feedback (increasing quality), and ultimately realizing higher profit margins (reduced costs). Furthermore, effective product development involves minimizing the resources (people, money, and time) required to deliver an appropriate mix of product features, performance, quality, price, and availability to customers. Despite the plethora of existing PMS for NPD, any measurement criteria concerning lean orientation have been found. This gap will be filled by the proposed PMS, described in the next section.

3 The Proposed PMS

Appropriate PM and its supporting systems are imperative to the successful implementation and execution of change initiatives. In the context of a lean transition, the interdisciplinary view required by strategic management highlights the need for wider frame of reference than the traditional notion of control or performance evaluation. Particularly, the adoption of lean practices led many companies to change traditional performance measures and the supporting system from strategic-level to activity-level as well as across functions and organizations to synchronize their operations.

NPD process is embodied in the product development organization, which is a grouping of people, utilizing tools and following established proceedings to create products in order to achieve specific goals. NPD deals with a certain level of complexity, which in many cases is determined by the number of interactions that occur within the process boundaries. Often, the more complex a NPD process becomes the more ambiguity and uncertainty exist. The approach used in developing this framework is to emphasize the value of engineering activities and eliminate waste by the identification of a set of metrics. A metric analysis permits a better management of this complexity providing the insights to build a notion of "how to think" rather than "what to think" in order to support integration and make the value flow for improving

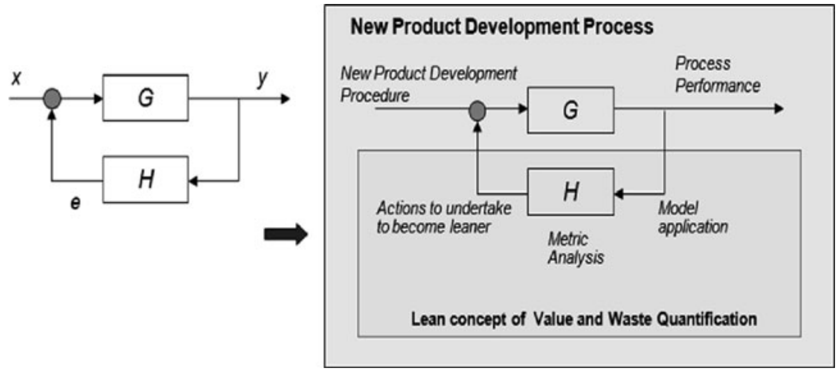

Fig. 1 Objectives of the PMS for a lean-oriented NPD

a NPD process. Let's make an analogy in order to visualize the expected effect of the framework proposed in this chapter. Figure 1 shows a negative feedback loop control system diagram. In this diagram, *G* and *H* are two systems that perform specific processes, transforming reference input signals into reference output signals. *G* is the main system, whose objective is to convert the input *x* into a desired output *y*. However, in the presence of noise, *G* can generate an output that differs from the desired output *y*. The function of *H*, then, is to sense the output of *G* and generate a compensation signal *e*. This signal, combined to input *x*, stimulates *G* so that the output approximates to the desired value of *y*. The analogy starts when *G* is visualized as a system that takes information about customer needs as input (*x*) and generates a signal that indicates the process performance level (*y*) once the product has been delivered. Product development process (*G*), as a grouping of several NPD activities, receives information about customer needs in order to satisfy them through the creation of products. It can be said that the success of one NPD process (*H*) lies on its capacity to assist the whole system to deliver the intended value and eliminate waste. A NPD process can be said to be successful if it detects discrepancies between the intended value delivery and the actual output and generates an effective engineering solution in terms of lean implementation (*e*). *H* senses the actual output delivered by *G* in order to generate a compensation signal (*e*) that stimulates *G* to improve its output. The success of *H* lies in its capacity to both accurately sense *y* (framework application) and deliver an effective compensation signal *e* (metric analysis).

The strategy proposed in this chapter is to provide a contribution to NPD PM to get a leanness process and to align the process toward the goals of a lean enterprise. From the above mentioned aspects, it was derived as starting point the adoption of the Balanced Scorecard (BS) approach. In fact, BS provides the possibility to create a PMS composed by relevant perspectives. Within each perspective, key objectives can be identified and measures can be associated with them. Then, the traditional BS developed by [19] has been reviewed, taking a lean point of view and focused on the NPD process. The lean point of view has been kept using as a reference the thirteen's principles for a lean NPD process defined by Liker and Morgan [8]. Each principle has been matched to a specific measurement perspective, in which the different values and wastes in the NPD process have been mapped creating a set of indicators taking value and waste notions into account.

The traditional BS has been reviewed taking a lean point of view and focusing on the NPD process. The resulting framework is a PMS with a set of more than 70 indicators, classified in 4 main perspectives (*Product*, *Process*, *Customer/Market*, *Finance*). The proposed perspectives are (Fig. 2):

- *Product/Project*, which includes the outcomes and the summarizing indicators of the other perspectives closely related to the product. The product is the central point of the proposed framework because it is not only the final output, but it is also the starting point of the NPD process. The measures include: price, time to market and modifications due to customer feedback. This perspective defines the value the customer perceives and quantifies the feedback as a result of the delivered value.

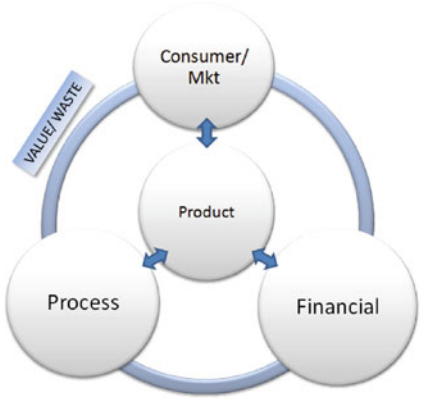

Fig. 2 The proposed PMS

- *Consumer/Market*. This perspective considers the customer and market involvement level from the need collection to the feedback analysis in order to realize high performing products. It focuses on the activity of need collection and to the NPD processes that request customer participation.
- *Process*. This perspective concerns with the processes and activities that develop the product starting from the customer need translation into requirements. It focuses on all the activities and key processes required for the company in order to excel at providing the value expected by the customers both effectively and efficiently. These can include both short-term and long-term objectives incorporating innovative process development, internal skills and capabilities that are required to support the value-creating internal processes in order to stimulate improvement. *Communication*, *People* and *Technology* are subsets of this perspective.
- *Financial*. This perspective takes into acCountryt the aspects belonging to the financial perspective of the traditional BS. In addition, it considers some ex-post indicators that are related to the launched products under constraints of time, cost and delays due to the approval of financial issues (e.g. request for investment authorization).

Perspectives are not separated boxes, but they must be seen connected with each other. For each perspective, a set of key measures has been drawn up. The set of the proposed indicators is the translation of the lean concepts of value and waste in order to identify the correct actions to become leaner in NPD. Indicators have been defined taking care of the two following aspects:

- *The proposed PMS has a specific architecture, organised into four areas*. For each perspective, a complete list of measures is accompanied by one or more indicators to provide an overall judgement of what is being measured.
- *The developed PMS is a universal customizable framework*. Its underlying idea is to collect the maximum possible number of indicators in order to build a framework that is capable of being applied to every NPD process. This is not a feasible idea, since proposed indicators in literature are several with no standardised taxonomy, and some measures need to be ad hoc for lean NPD process. The proposed framework is made up of indicators coming from the literature, ad hoc developed indicators (which translates the qualitative lean principles into quantitative indicators) and based on empirical analysis (e.g. industrial case study presented in Sect. 4). Then a company can customize the framework defining its proper declination, instantiated in a customized dashboard.

More than 70 indicators have been defined, and they have been classified according to different categories:

- *Value-Waste*, which reflects the lean thinking beyond the development of the framework.
- *Time-Efficacy-Efficiency*, which considers the traditional aspects of NPD PM.
- *Primitive versus Derived indicators*. The primitive indicators refer to a single data collection, and they are absolute and punctual numbers. The derived indicators are composed of two or more data collections, and most of them are a ratio of two data collections, while some of them consider also the temporal aspect of the collection giving information about the timeliness of data.
- *Real time versus Ex Post indicators*. Some indicators are a real time sign of how the process is performing. They can be measured as soon as the activity ends giving instructions on how the process is performing, and how probably will evolve the outputs of the following activities. They are reactive indicators in order to undertake preventive actions for improving the performance of the downstream activities. The other indicators are ex-post, they can be measured only when the entire process ends providing with a feedback of how it has been performed, majority of them belong to the financial and product perspectives, which can't be measured otherwise.
- *Absolute versus Relative measures*. For each measure and for each way to evaluate it, the absolute value is provided. However, a comparison with reference values is needed in order to connect actual results to database's ones. Some indicators can also be related to reference values or previous value to provide a deeper analysis of measured information.

For each indicator, a table like Table 1 has been defined.

Within a company, it is impossible to adopt all the proposed indicators, but generally a decision maker might focus his/her attention on the most relevant performances, using a limited list of indicators, grouped in an easy-to-read dashboard. Such a panel should be tailored according to the organization needs so that the selected indicators reflect the mission of the NPD process.

Figure 3 shows the suggested procedure for defining the customized dashboard. Process mapping is especially useful to identify where bottlenecks occur and hence where performance measures can help in improving the process. The selection of indicators is based on these considerations and the measurable indicators in the company. Then, the development of the dashboard is based on the allocation of the indicators to the different phases of NPD process. The next step considers the aggregation of indicators both in vertical (to consider the performance of each phase of NPD process)

Table 1 Example of an indicator table

Measure	Need collection completeness
INDICATOR # 1	*Number of identified customer needs*
Description	It measures the level of completeness of customers' need collection by measuring the number of identified customer needs: more this value increase, more the need collection is complete and this can positively affect value
Unit of measurement	Integer number
Responsibility	Team (e.g. Marketing)
Target	Value X
Min	Value Y
Max	Value Z
Frequency of data collection	Every time a NPD project starts and data collection phase is finished.
Relevance and notes	The average number of needs collected in the *n* last NPD projects (*n* has to be defined depending on each case) can be considered as a benchmark for further considerations. Comparing the number of identified customer needs with the average previous one, if the indicator is near 1 it means that collected data are complete, if it is >1 the process is getting better. This indicator must be evaluated with extreme attention; in particular the analyst should be also observe the trend of previous data and not only the average value.

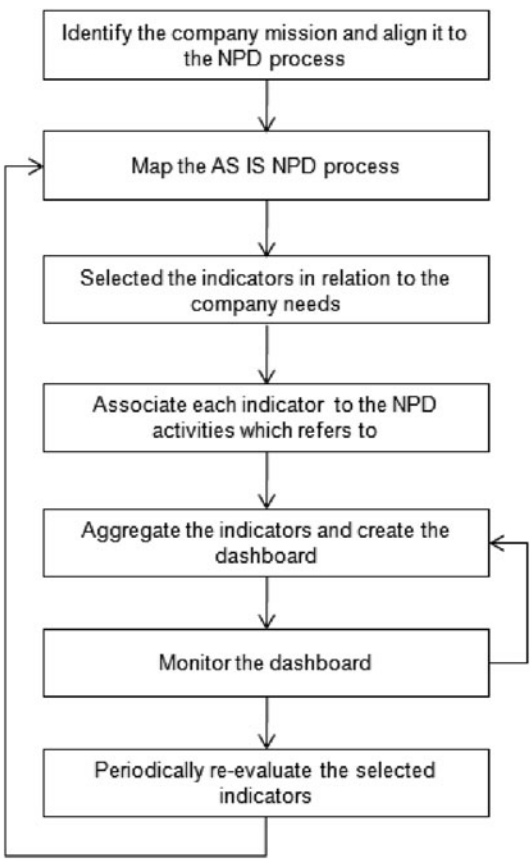

Fig. 3 Dashboard creation procedure

and cross phases (to consider the performance of the whole NPD process) directions, to fit to single company's needs. Aggregation can be realized in different ways; as the analysis of the literature revealed, a well applied method is Analytical Hierarchical Process (AHP) technique [34], capable to compare measures or indicators in pairs and obtain a weight for each measure/indicator according to the interviewees' opinion.

4 Case Study

The developed framework has been exemplified through the application within the NPD process of a household appliance manufacturing company. The implementation of the PMS has been done in two steps in order to analyse the applicability of the framework as a set of indicators and to verify the development of the dashboard.

The applicability of the framework points out the measurability of the 70 developed indicators, 77% of them are measurable and the rest are immeasurable indicators. The latter can be divided into three categories: interesting indicators (27%) including those indicators that are difficult or impossible to quantify but it should be useful to measure, not relevant indicators (60%) that are useless to the company and indicators that are derivable from others (13%). The majority of immeasurable indicators belong to the *Process* perspective since a general NPD process is variable for definition and in some aspects, even if interesting, hardly quantifiable. Moving to the development of the dashboard, the indicators have been selected from the measurable ones, and they represent the 50% of them and 39% of the total proposed indicators. The selected indicators mainly belong to the *Process* perspective since it is the most important area to monitor in order to undertake corrective actions. The second most considered perspective is the *Customer/Market* one since the customer is an actor of the process that must be involved. Some of the selected indicators are shown in Table 2.

Table 2 Indicators selected to develop the dashboard of the business case

#	Selected indicators
3	# of considered customer needs/ # of identified customer needs (screening)
5	# of considered needs/ time spent to collect
6	(considered needs – abandoned needs) /considered needs
7	# of requirements from client/ total # of requirements
9	# of field tests/total # of tests
10	1– (# of modified requirements due to customer involvement/ total # of modified requirements)
18	# of standard tasks (what to do)/ total # of tasks
19	# of activities out of scheduling/ total # of activities
21	supplier lead time for part development/expected supplier lead time for part development
22	# of parts developed in co-design/ total # of parts developed
23	time spent with supplier/development time
24	# of different used formats
26	$\sum$ activity duration/ development time
28	# of tested parts/ # of supposed critical parts
30	average prototyping speed = $\sum$ time for prototyping/total # of prototypes
31	$\sum$(delivery time- demanding time)/ # requested data
33	# of on-schedule started tasks/ total # of tasks
35	# of people with full access to product data/total # of people involved in the process
39	Data coming for previous projects/total used data
40	# of duplications on document variations
43	# of respected technical specifications/total # of specifications
44	# of times that a design had to be reworked
47	# of alternative solutions of new designs
47	Average # of parts per product
53	Time to approve projects = project presentation time – project approval time
54	NPD costs/NPD budget
65	Time to Market

5 Conclusions

In the NPD process, many kinds of metrics are used to measure different aspects of the development activities. Some of them can measure the product design characteristics, while others can be used to measure the resources that the organizations allocate to each activity or time of development, which is typical considered as a key for NPD success. The indicators belonging to the framework aren't an assessment on how lean is the NPD process, since there are some effective tools developed to do that (e.g. LESAT), but they are the translation of the lean concepts of value and waste and have been proposed to identify the correct actions to undertake in order to become leaner in NPD. The most important difference between an assessment tool such as LESAT and the developed set of performance indicators is that the first provides a qualitative measurement of the actual level of lean of a company in NPD. The second provides the instruction (in lean terms) for the continuous improvement in NPD process. The first step for using this framework is to understand how key performance measures can guide and drive a company towards superior lean results in NPD process. In pursuing this aim, the dashboard tries to easily outline the areas requiring corrective actions in order to eliminate waste and increase value, beyond a mere aggregate numeric value of the lean state since it would be ineffective. The reason behind this consideration is that the whole composed by the dashboard, its analysis and associations between indicators can give a lean interpretation of the ongoing process. Lean refers to a wide process, and it is interesting to know the direction the process should follow to become lean and where it should be optimized. The indicators and the dashboard tailored on an organization's needs as a whole are explanatory of the lean paradigm; by monitoring the dashboard in the long term probably will also emerge, which are the indicators that better point out the effort in the lean transition.

To have further confidentially of the validity of the model, some industrial experts have been asked to evaluate the developed model. The feedback provided both from the case study and the experts' opinions show that:

- the model covers the most part of the NPD process;
- it is applicable (in the business case 77% of indicators were measurable);
- it is an attempt to quantify value and waste;
- it includes the advantages of flexibility and adaptability to enterprises' needs that derive from the adoption of the BS and the development of the dashboard.

Nevertheless, the weakness of the model is due to the lack of a methodology to identify easily which indicators are mostly representative of the lean state; the perspectives of the developed BC should also be adaptable to include possible extensions of the NPD boundaries. Further directions of the research are the development of different kinds of aggregations and the validation of the PMS on other companies.

The presented framework has been created within the LeanPPD project, a European Commission co-funded project, made by 11 partners, and duration of 4 years. The aim of LeanPPD is to develop a new model based on lean thinking that will consider the entire product lifecycle, providing a knowledge-based environment to support value creation to customers in terms of innovation and customisation, quality as well as sustainable and affordable products. This will be called Lean Product and Process Development (LeanPPD) paradigm.

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A Framework for Assessing the Reliability of Mechatronic Systems

A. Coulibaly and E. Ostrosi

Abstract This chapter proposes a framework for mechatronic systems reliability assessment at early stage of the design process. The approach provides to designers the product reliability indicator by using a semantic model that includes data related to its components characteristics and to their interactions. We focus on complex mechatronic systems consisting of sub-systems made of mechanical components, electronic devices and software modules. The paper presents two main problems to face for assessing complex products reliability: what decomposition strategy to use and how to estimate the components reliability. Then we estimate the product global reliability by considering separately mechanical components, electronic devices and the software. To test the approach, an application is outlined to estimate the reliability of a hard disk.

Keywords Mechatronic system · Reliability · Behavioural modeling · Software reliability

1 Introduction

Reliability engineering is the function of analyzing the expected or actual reliability of a product, process or service, and identifying the actions to reduce failures or mitigate their effects. Engineers analyzing reliability typically carry out reliability predictions, FMEA or FMECA, design testing programs, monitor and analyze field failures, and suggest design or manufacturing changes. The overall goal of reliability engineering is to make products and systems more reliable in order to reduce repairs, lower costs, and to maintain the company's reputation. To meet this goal best, reliability engineering should be done at all levels of design and production, with all stakeholders involved. Nowadays, current CAD and CAE systems provide good functionalities for products geometric modeling, structural and dynamic analysis. Most of these systems are aimed to functional and structural performances validation by numerical simulation. However there is a lack of efficient tools for evaluation of new products behavioral performances like reliability, maintainability, safety or recyclability. The main reason of this deficiency is that such characteristics are semantically specified; so additional information (data, knowledge and rules) are required to assess them.

These last years some investigations have been done in developing solutions for reliability and maintainability prediction at the early design process [1, 2]. To predict products reliability and maintainability, software packages like Relex Software [3] or ITEM Software [4] are widely used in various companies, more especially by aeronautic and automotive constructors. But these tools are not connected to a CAD system to allow reliability assessment using the product model. For brand new and innovative products made of new design architectures and new components, new efficient assessment tools are required.

Reliability and maintainability estimation is a crucial problem when designing complex mechatronic products that consist of different subsystems including mechanical elements, electronic equipments and software. This is the case in various industrial sectors like automotive, aeronautics, nuclear power plants, NC machine tools, and even commonly used products like washing machines, copiers, CAD plotters [5].

To face this demand, many tools using virtual reality technologies are proposed to verify new product functionalities, to test its ergonomics and to analyze its maintainability [1]. But such systems are mainly designed for mechanical products. In addition, virtual reality platforms are often very expensive and complex to use during design process. So such systems are used by a few big manufacturers in the design of automotives, aircrafts or nuclear plants.

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In this chapter we propose an approach for prediction of a complex product Reliability based on components reliability and criticality characteristics. The approach is based on the Semantic-FSB product behavioral modeling approach proposed in [6]. In Sect. 2 we define the mechatronic products structural and technological complexity notions. Section 3 describes the complex products decomposition strategies. In Sect. 4, we outline the Reliability assessment approach in the case of multi-components products. Sections 5, 6 and 7 deal with respectively assessment of mechanical, electronic and software components reliability. Section 8 defines the components criticality notion and attribution procedure. Section 9 describes the semantic matrix input data and its construction procedure. For illustration, an application concerning a hard disk is outlined in Sect. 10. The main results and some future developments are given in conclusion.

2 Mechatronic Systems Complexity

Mechatronic products are commonly defined as products that consist of different subsystems including mechanical elements, electronic equipments and software modules. We consider as complex products such products made of mechanical components controlled by intelligent systems consisting of electronic equipments and software.

Estimating the global reliability of these products is of crucial interest in the context of industrial competition. For traditional basic mechanical products, the reliability is estimated using statistical databases [3, 7, 8] and the maintainability is determined as the MTTR (*Mean Time To Repair*) when some critical components fail. For complex mechatronic products, very often, the reliability is determined using the same approach by analyzing separately the components behaviors. For new products, if statistical data are not available, the reliability is estimated using Accelerated Life Testing techniques on samples of prototypes. If no prototypes are available, the reliability is calculated by simulations made on some critical components that may be mechanical parts either electronic equipments. Generally, the software reliability is skipped in the assessment.

Here, we attempt to take into account all the three kinds of reliability and to consider components criticality. To this purpose, we distinguish two kinds of complexity: structural complexity and the technological complexity.

2.1 Technological Complexity

This is another point of view of the product complexity. The technological complexity is an indicator on the different technologies used in a product. A basic mechanical product made of only mechanical components is assumed as less complex compared to a mechatronic product containing different kinds of components: mechanical elements, electronic devices and software modules (in micro-controllers, or executed by a computer) as shown in Fig. 1.

So, a mechatronic system consists of 4 families of components: mechanical components, electronic devices, Software and sensors as shown in Fig. 2 that represents a partial view of a gas turbine control system [*source*, 9].

More generally, a mechatronic system can be modeled as shown in Fig. 3.

Traditionally, at design stage the sensors are assumed to be available at the market and the design engineer has just to choice the suitable sensors.

So, we consider here that in a mechatronic product, each component C_i may be in one of the three families shown in Table 1.

So, a 111-Product is a typical mechatronic product, a 110-product is an electromechanical product and a 100-product is a basic mechanical product.

So, the product reliability assessment depends on these two kinds of complexity. In the next section we discuss about the structural complexity.

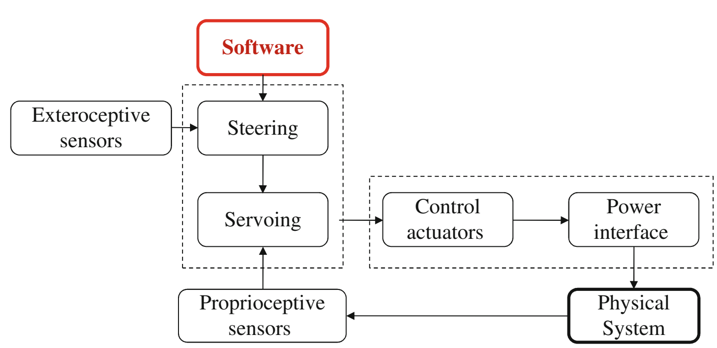

Fig. 1 Mechatronic system conceptual model

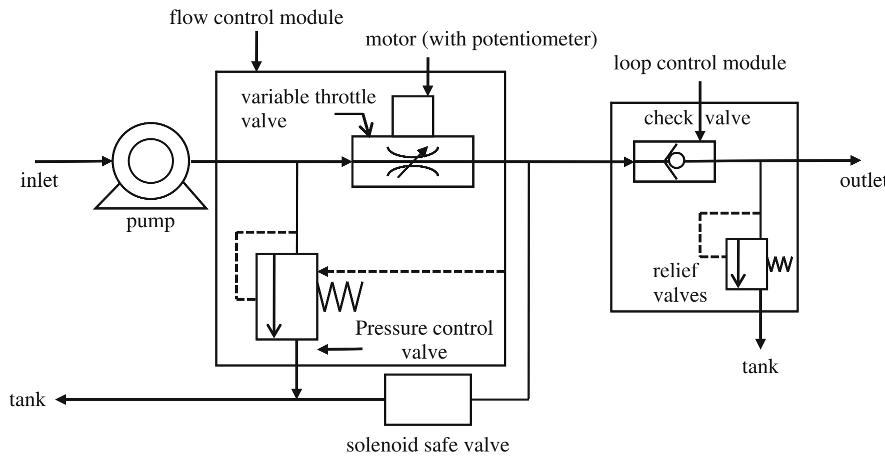

Fig. 2 Partial view of gas turbine control system

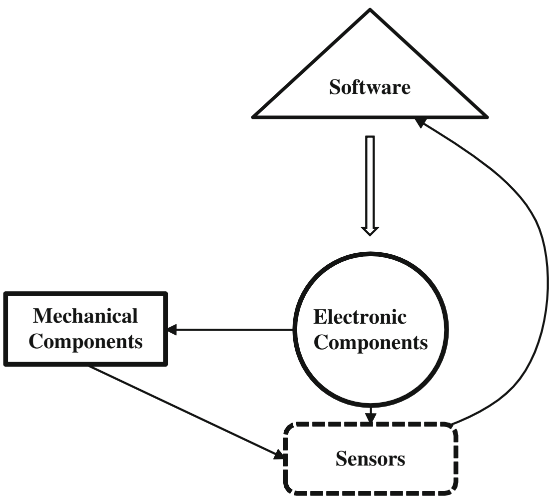

Fig. 3 Technological complexity

Table 1 Technological complexity

	Product complexity		
	P_1	P_2	P_3
Mechanical components	1	1	1
Electronic devices	0	1	1
Software modules	0	0	1

2.2 Structural Complexity

A product is structurally defined as a set of components (C) and a set of fasteners (F).

$$\text{Product} = C \cup F$$

where:

$$C = \{C_1, C_2, \cdots, C_n\}$$

$$F = \{f_1, f_2, \cdots, f_m\}$$

A component may be a single part (a brace, a strap, a gear, a pulley, a breech, etc...) or a sub-assembly consisting of a certain number of parts (an alternator, a gearbox, a wing of plane, an electronic card, a hard disk, etc...).

Fasteners may be standard mechanical accessories (nuts, pins, screws...) or chemical links (soldering, glue, etc...).

The product structural complexity depends on different characteristics like: the number of components, or parts geometric morphology, or sub-assemblies configurations, or the types of links between components, etc.... So, structural complexity seems to be a subjective notion that is usually related to the number of components placed into a given volume (Fig. 4).

Then it is commonly considered that the more the number of components by unit of volume is high, the more the structural complexity is high. The product configurations in terms of components diversity in shape and material is also an indicator for structural complexity. We are focused here on the

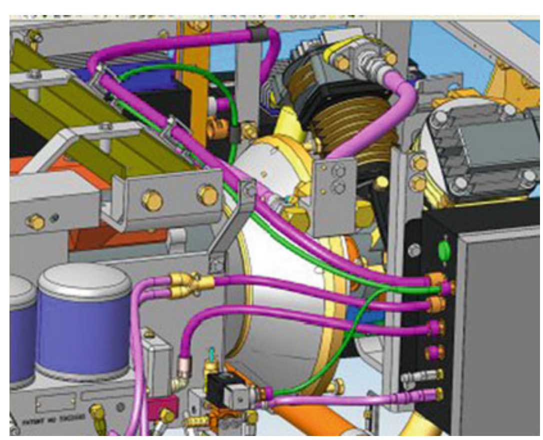

Fig. 4 Structural complexity

number of components usually called structural density. This characteristic depends on the level of product decomposition as discussed in Sect. 3.

3 System Decomposition Strategy

We consider complex products consisting of subsystems that contain at least one or more parts. Figure 5 shows a typical structure of a product decomposition procedure.

The product is structurally decomposed by the design team into components according to different points of view: structural, functional or behavioral. The pertinence of the structural decomposition level depends on different goals like product functional structure, manufacturing and assembling processes or commercial packaging. From the functional point of view, the product is decomposed into functional sub-assemblies that match to its main functions. If manufacturing aspects are considered, the structural decomposition will correspond to other sub-assemblies. If commercial packaging is considered, the product will be decomposed in such a way that spares are provided easily. For complex products like cars or planes the decomposition strategy depends on all these three functional, manufacturing and commercial objectives. So the choice of a suitable decomposition level is a key problem that determines the behavioural performance indicator pertinence.

4 System Reliability Estimation

The product reliability level required is usually specified in the design specifications document. This is a crucial point that is often skipped at detailed design level. In the next section we present an approach to estimate this characteristic. In this study, we consider the case of components in series.

4.1 Product Reliability Assessment Procedure

The procedure presented in Fig. 6 begins from the decomposition step, and then the components reliability is determined.

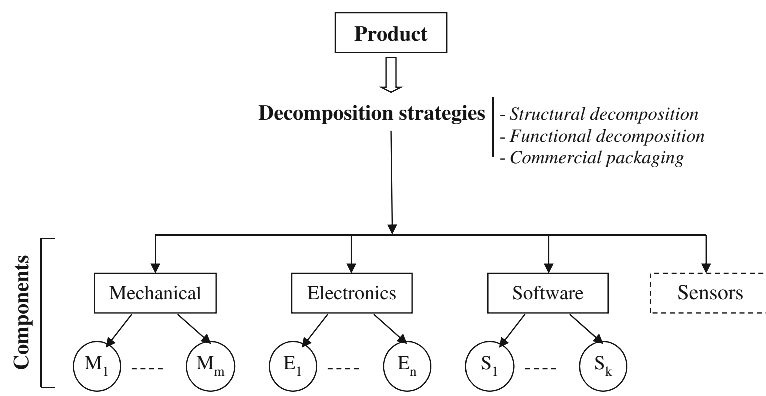

Fig. 5 Product decomposition

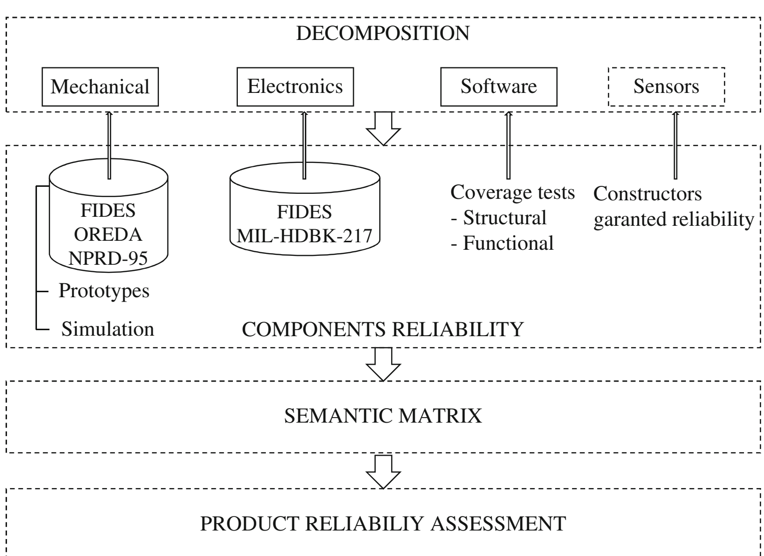

Fig. 6 Reliability assessment procedure

This data is used into a semantic matrix to analyze their interrelationships, the product global reliability and maintainability.

For a multi-components product with no redundancy, its global reliability is expressed by:

$$R(t) = \prod_{i=1}^{n} R_i(t) \tag{1}$$

where R_i is the reliability of a component C_i, it is defined as the probability that this component performs its function in specific given conditions over its life time, T. R_i is expressed as follows:

$$R_i(t) = \Pr(t < T) \tag{2}$$

In the next sections we present solutions for defining reliability R_i for the different kinds of components.

4.2 Components Reliability

Each component may contain mechanical elements, or with additional electronic devices and software. So, the component C_i reliability is expressed by:

$$R(C_i) = R_{\text{mech}} \times R_{\text{elec}} \times R_{\text{soft}} \tag{3}$$

where R_{mech}, R_{elec} and R_{soft} represent respectively, mechanical, electronic and software elements reliability, as in Table 2 where:

C_{mech} represents mechanical components,
C_{elec} are electronic devices and
C_{soft} are software components

e.g. in the case of a product consisting of only mechanical components, its reliability is equal to the reliability of R_{mech}. In such a case, the reliability of electronic and software components are respectively equal to 100%, i.e.: 1.

Then, according to if the component's constituents are standard or new parts, we have to use one of the following reliability estimation existing approaches.

In the three following sections we present solutions for defining reliability for different types of components.

Table 2 Component, C_i, reliability

	Components		
	C_{mech}	C_{elec}	C_{soft}
Mechanical parts	R_{mech}	R_{mech}	R_{mech}
Electronic cards	1	R_{elec}	R_{elec}
Software modules	1	1	R_{soft}

5 Mechanical Components Reliability

Mechanical systems reliability depends on design and on utilization conditions. Moreover, failure mechanisms as fatigue or stress yield systems ageing. The reliability databases are not allowed to deal with these particularities because of generic and constant failure rates. Many uncertainties in reliability predictions can be due to the use of these databases. A failure rate modeling is introduced in different research investigations and aims at taking into account both time and influencing factors [10]. In this chapter, we mainly consider the nominal behavior of standard mechanical components, prototypes and new innovative components.

5.1 Standard Components Reliability

For standard mechanical and other non-electronic components, there are guides for the evaluation of some elementary components (screws, valves, gaskets, etc...). We distinguish some reliability databases, presented below.

- OREDA (Offshore Reliability Data) published in 1985: database of reliability built from the experience of return on companies that operate offshore platforms. The data relate to industrial materials, mainly electromechanical related to oil extraction: compressors, heat exchangers, generators, various valves, boilers, pumps, evaporators, etc... [11].
- EIREDA (European Industry Reliability Data Bank): database of reliability built from the return on experience of European companies, mainly from the chemical, materials for electromechanical energy consuming electric fans, evaporators, heat exchangers, pumps, compressors [7].
- NPRD-95 (Non-electronic Parts Reliability Data): database of reliability built from the return on experience of major U.S. agencies such as NASA and the U.S. Navy. The reliability data concern the mechanical and electromechanical components used in military equipment mainly [8].

So, for standard mechanical components, we use these reliability databases as input to estimation of the mechanical subsystems reliability.

5.2 Prototypes Components Reliability

For new components with prototypes, reliability may be estimated using Accelerated Life Testing (ALT) technique on components by placing them in a experimental platform in severe working conditions under environmental stress (temperature and vibration, etc...) than in normal utilization conditions. In these conditions, because of existence of vibration and temperature effects, most of real failure types will be appeared in the products. We can diagnose these failures in order to treat and remove them from the products and finally to increase the reliability of the products [6].

5.3 Virtual Components Reliability

Virtual components are new designed elements with just a CAD model without any physical prototypes. For such components, Reliability estimation may be performed using Virtual Samples Tests by numerical simulation. In [12] the Strain(S)/Stress (L) method is used to estimate product components reliability. This is an approach based on the finite element method simulation. Stresses and strains are defined by their probability density function f_S and f_L. The reliability is defined as the probability that the Stress remains lower than the Strain. The functions f_S and f_L are determined using virtual samples tests technique. For each component the virtual samples are generated from design parameters and characteristics relative to the material properties variability and geometric dimensions tolerances. And then the reliability values are assigned to the different components as shown in Fig. 7.

The two following sections present successively how to assess the reliability for the electronic devices and the software.

6 Electronic Devices Reliability

Milton Ohring, in [1], offers a complete coverage of most major topics related to the performance and failure of materials used in electronic devices and electronics packaging. With a focus on statistically predicting failure and product yields, this book can help the design engineers, and quality control service all better understand the common mechanisms that lead to electronics materials failures. This book covers all major types of electronics materials degradation and their causes, including dielectric breakdown, hot-electron effects, electrostatic discharge, corrosion, and failure of contacts and solder joints. In addition there are many reliability databases about electronics equipments from different manufacturers [5]. In practice, different reliability guides are used to estimate electronic components reliability. The original reliability prediction handbook was MIL-HDBK-217, the Military Handbook for "Reliability Prediction of Electronic Equipment". MIL-HDBK-217 is published by the US Department of Defense, based on work done by the Reliability Analysis Center and Rome Laboratory at Griffiss AFB, NY [2]. This handbook contains failure rate models for the various part types used in electronic systems, such as ICs, transistors, diodes, resistors, capacitors, relays, switches, connectors, etc. These failure rate models are based on the best field data that could be obtained for a wide variety of parts and systems; this data is then analyzed and massaged, with many simplifying assumptions thrown in, to create usable models. The latest version of MIL-HDBK-217 is MIL-HDBK-217F, Notice 2 (217F-2). Design engineers can get a copy of MIL-HDBK-217F-2 from any source that provides Mil Specs, Mil Standards, Mil Handbooks, etc.

Since this most commonly used guide is now obsolete and is not maintained for over 10 years, a European project, FIDES is under development for completing calculations of predictive reliability for electronic components and systems [13]. This evaluation is usually expressed in FIT (number of failures per 10ˆ9 h) or MTBF (mean time between failures). These reliability data are the basis of studies of maintainability (sizing inventory maintenance in operational conditions), availability and security. This project was initiated by the DGA (Déléguation Générale pour l'Armement) and conducted in 2004 by a consortium of eight European manufacturers in the defense and aerospace industry: Airbus France, Eurocopter, Nexter Electronics, MBDA Missile Systems, Thales Services, Thales Airborne Systems, Thales Avionics and Thales Underwater Systems.

These guides are commonly considered as reliable for electronic devices reliability prediction. So, it is strongly recommend using these reliability guides.

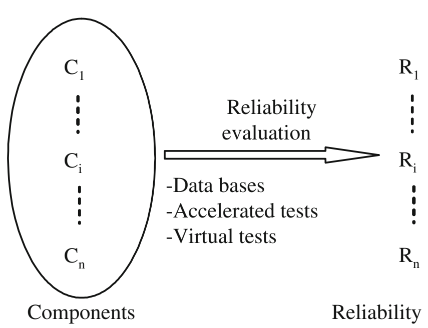

Fig. 7 Components reliability estimation

7 Software Reliability

The two previous sections show that reliability is a well-known characteristic in the material world. It is related to the uptime before failure of a component. For instance, a mechanical component may be subject to wear phenomena. An electronic hardware can be submitted to dielectric breakdown. Software is not subject to such degradations but has an unknown number of faults. So, reliability is a concept still uneasy to define for the software. It can translate the overall confidence one places in the software. It can also be estimated either qualitatively or quantitatively. Indeed, some will consider that software is reliable when all the code has been covered in testing, others will measure the time of error free operation of software.

The reliability of software is defined by different standardization institutions by:

- The AFNOR standard Z 67-102: all attributes on the ability of software to maintain service level in specific conditions and for a specified period.
- The AFNOR standard Z 61-102: ability of a program to perform without failure all the functions specified in a document of reference in an operational environment to a particular use.
- The IEEE 610.12-1990: the probability for a failure-free operation of a program for a specified set of operating conditions.

The commonly accepted definition of reliability is the probability that the software works without error in a given environment during a given period.

In her PhD thesis devoted to software validation, Le Guen presents many approaches to reliability modeling and calculation [14]. Most of estimation models presented in this work are based on an observation of black box software. However, there is an approach based on the structure of the software. Here, we consider this latter approach proposed in [15] that uses a Markov chain structure to model the software. The software is then assumed to consist of K components. The process of failure of each component is a Poisson process. The software activation is modeled by a Markov chain of

$$(K + 1) \text{ states.}$$

where:

- in the K first states the system correctly performs the functions required;
- in the $(K + 1)$-th state the system is in failure.

The different states are defined as follows:

- For $i = 1$ to K the system is in state i if component i is active and if no failure occurs during the execution of component i;
- The condition $(K+1)$ is the absorbing state for which the service is interrupted.

In this state two processes are then superimposed the solicitation process and the process of failure.

- The process of failure of component i is a Poisson process with failure rate λ_i.
- If (π_i), $i = 1, \ldots, K$ is the vector of asymptotic probabilities of the Markov chain on the execution, the resulting process is a Poisson process with parameter λ_{eq} can be approximated by:

$$\lambda_{eq} = \sum_{i=1}^{z} \pi_i \lambda_i \quad (4)$$

In this approach, one of the problems of the test phase is linked to the notion of coverage. How can we quantify test coverage compared to application functionality, and how can we assess the states that are not adequately covered by the tests?

Two notions of tests coverage are commonly considered to answer to these questions: the structural coverage and functional coverage.

- The structural coverage, assumes that the source code is available for the different software modules. This coverage validation is very expensive and does not necessarily detect all types of errors [16].
- The functional coverage is not complete and is based in most cases uses not sufficiently formalized.

These tests strategies are commonly accepted in the industry but are generally very costly to achieve and do not allow to completely prevent against failures.

It is therefore necessary to find sufficient criteria for coverage to have a minimum limit for the probability of not finding error based on different features used.

8 Components Criticality Attribution

For a given product, each components criticality is a measure of the relative importance and influence of the component with respect to the product behaviour. The criticality is related to the functional point of view or to safety considerations. We define a criticality scale laying from 1 for the most critical level to 0 (zero) for the non critical components.

For reliability and maintainability assessment, functional and safety criteria are generally considered [17–19]. The attribution of the components criticality is decided by the design office advised by the project experts.

So, a component is affected with a criticality level 1 if its failure implies the stop of the product functioning or requires immediate stop because of safety reasons. A component

Table 3 Component criticality status

Criticality status	Mechanical	Electronic	Software
Normal	1	1	1
Survival	1	1	0
	1	0	1
	1	0	0
Stop	0	1	1
0	1	0	
0	0	1	
Crash	0	0	0

which failure has no consequence on the functional performance and no safety risk will be affected with the lowest criticality level, 0.

We define in Table 3 the component criticality in relation to the 8 failure status that may occur while using a complex product. The failure mode for component C_i is notated $C_i(m,e,s)$ where m, e and s are binary variables with value 0 if the corresponding element is in failure and 1 if it is operational. Then we define 4 typical criticality status as mentioned in the table. In a *Normal* status, a component is fully operational and is notated $C_i(1,1,1)$. A component, $C_i(0,0,0)$, in a *Crash* status has all its three elements down. A component in a *Survival* status has its mechanical element operational but one at least of its electronic or software is in failure. In a *Stop* status the component has its mechanical element in failure and no matter if the electronic and/or software constituents are operational or not.

So at a given instant, each component of a product is affected with a criticality status. At design stage these different status may be attributed by experts [20], as shown in Fig. 8.

After the different components reliability and criticality are attributed, we outline in the next section the semantic matrix construction procedure using these data.

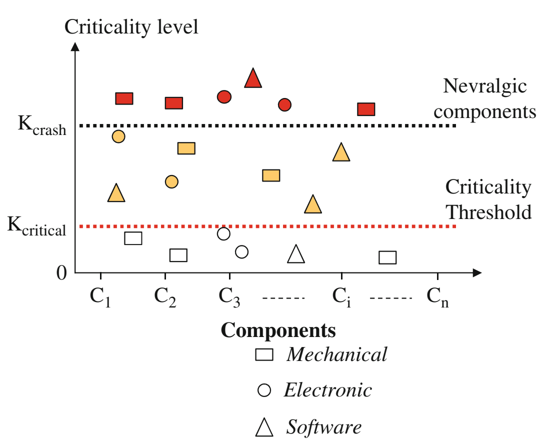

Fig. 8 Components criticality, K_i

9 Product Semantic Matrix

The product is represented with a Semantic Matrix consisting of the following inputs: part list, reliability and criticality data.

9.1 The Inputs

The product design solution is assumed to consist of multi-components structure built by a set of components which are bind together by different types of assembly links. If some links consist of detachable fasteners, the product can be splitted down into sub-systems, or single parts, by removing the links. The product Structure is represented with a CAD model that specifies the geometry and dimensions of the different components and their topological interrelationships. To build the S-FSB model, the CAD model is enriched with additional semantic data concerning non graphic characteristics like material properties, functional criticality (K_i), reliability (R_i). We represent these data by the Product Semantic Matrix representation as shown in Fig. 9.

9.2 Semantic Matrix Construction

In the Semantic Matrix representation a n-components product is described by its C_i (with $i = 1 \ldots n$) components.

The link type for every couple of components $(C_i, C_j) = L_k$ is the assembly type between components C_i and C_j. L_k takes different values depending on how the two components are assembled [21]. K_i, and R_i stand respectively for the functional criticality and reliability associated to component C_i. Beyond the type of assembly, the semantic matrix can be extended to include other kinds of connections that could be defined between components to describe either physical interactions or functional relationships.

The functional criticality level is estimated by the designer depending on the relative importance of the different components. K_0 is the threshold value of criticality used to identify neuralgic components to be considered for maintainability indicator calculation. R_0 is the product global reliability threshold fixed in the requirements document.

The P_i diagonal elements represent the components semantic properties. P_i is a vector of various types of information like: material properties, surface state, heat treatments, surface treatments ... So, for a given component C_i, the P_i vector is the set of attributes related the C_i component.

Then, for a mechanical component, P_i is defined as follows:

Fig. 9 Product semantic matrix

Components	C_1	C_2	-	-	C_j	-	-	-	C_n	**Reliability**	**Criticality**
C_1	P_1	2	0	1	0	1	5	2	0	R_1	K_1
C_2		P_2	2	1	0	0	0	2	0	R_2	K_2
-			-	0	0	0	0	2	0	-	-
-				-	1	0	0	2	0	-	-
-					-	1	0	2	0	-	-
C_i	LinkType (C_i , C_1) = Li - 1				LinkType (C_i, C_j) = Li - j	-	1	2	0	R_i	K_i
-							-	2	0	-	-
-								-	5	-	-
C_n									P_n	R_n	K_n
Number links	d_1	d_2	-	-	dj	-	-	-	dn	$\mathbf{R_0}$ (threshold)	$\mathbf{K_0}$ (threshold)

$$P_i = \text{Vector (material, surface state, heat treatment, weight, surface treatment ....)} \quad (5)$$

Such vector can be extended to electronic and software components as follows:

For electronic components, P_i contains information like:

$$P_i = \text{Vector (input signal, output signal, number of surface components, number of inserted components ...)}$$

For software, P_i can be defined considering its structural description and input and output data flow:

$$P_i = \text{Vector (classes, internal relationships, input data, output data ...)}$$

From reliability and criticality data gathered in the semantic matrix, we can calculate the product's reliability indicators by considering the components criticality levels as shown in Fig. 8.

9.3 Product Reliability Indicators

If the mechatronic product contains M mechanical components, E electronic devices and S software modules, the reliability indicators can be determined as follows.

The first indicator R_{critical} is calculated taking into account components whose criticality is higher than the criticality threshold.

$$R_{\text{critical}} = \left[\prod_{i=1}^{M} R\left(C_i^{\text{mech}}\right)\right] \cdot \left[\prod_{i=1}^{E} R\left(C_i^{\text{elect}}\right)\right] \cdot \left[\prod_{i=1}^{S} R\left(C_i^{\text{soft}}\right)\right]$$

$$\text{for components with } K_i \geqslant K_{\text{critical}}$$

The second indicator R_{crash} is assessed by considering major components whose failure will cause the crash of the product. Such components have a criticality higher than the crash threshold criticality, K_{crash}. The reliability expression is the same as for R_{critical} but the criticality threshold is different.

$$R_{\text{crash}} = \left[\prod_{i=1}^{M} R\left(C_i^{\text{mech}}\right)\right] \cdot \left[\prod_{i=1}^{E} R\left(C_i^{\text{elect}}\right)\right] \cdot \left[\prod_{i=1}^{S} R\left(C_i^{\text{soft}}\right)\right]$$

$$\text{for components with } K_i \geqslant K_{\text{crash}}$$

These indicators will help the design team to consider alternative solutions to improve the overall reliability of the product.

As illustration, Fig. 10 shows the example of a hard disk that must be designed to fulfill various utilization conditions requirements.

10 Application for Hard Disk Reliability

A hard disk is typically a mechatronic system that is used for data storage in various high tech products. A part from its traditional use in computers the hard disk is widely used in different other equipments such as printers, CAD plotters, cameras, mobile phones, PDA, DVD players, game consoles. So, this product has become a critical component in the choice of these products. Therefore, it is crucial to ensure a high reliability level to hard disk.

Using software package for scientific computation like Matlab or similar a free open-source solution like Scilab, it is possible to model such a product [22, 23] and to analyze it behavior using software like LabView [11, 24]. To apply approach presented above in this case, we have to define the product part list for mechanical components, electronic sub-systems and for the software (drivers and applications).

As shown in Fig. 10, a hard disk includes:

- Mechanical components: arm, Spindle motor, Arm motor;
- Electronic devices: electronic control card, interface, reading/writing head, magnetic disk; and

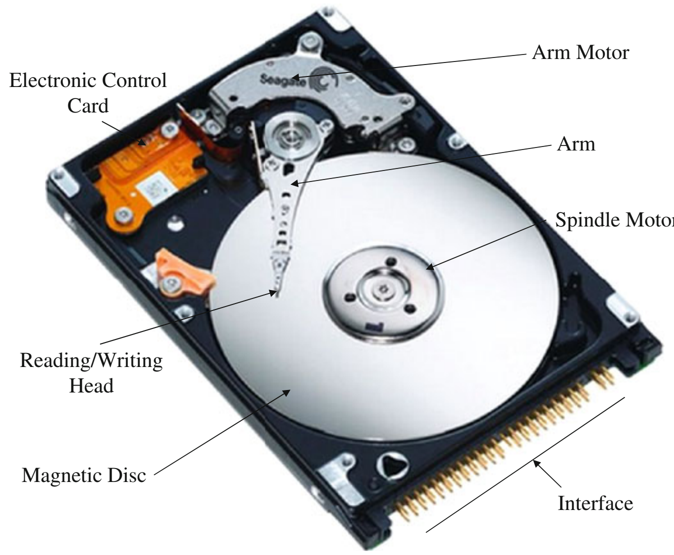

Fig. 10 Hard disc structure

– Software: firmware and drivers required to control its internal operations and the communications with the external processors.

To evaluate the whole reliability of this hard disk, we consider the reliability of its different components and then we apply the procedure presented in Fig. 6.

11 Conclusion and Future Works

This chapter presents an approach for assessment of reliability and criticality for complex mechatronic products at early design stage using CAD model enriched with behavioral semantic data. Our approach attempts to take into account the product structural and technological complexity. This may be a helpful tool to assist designers to predict product reliability that is traditionally evaluated after design process. The different components reliability is obtained from the databases mentioned previously. At first approximation, our study is based on some limitations: the reliability is evaluated by considering the case of components in series. For complex products, it is necessary to consider a general product structure including both parallel and series configurations. The illustrating example outlined here shows the feasibility of our approach. The hard disk global reliability can be estimated using these reliability data. In future works, the feedback of reliability indicators to product design will be considered to integrate our approach into a CAD system for allowing reliability estimation directly in such a design environment.

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Rapid Product Development, Reverse Engineering, Virtual Reality for Global Product Development

Reverse Engineering for Incorporation Stage of Forming Dies

C. Schoene, D. Suesse, R. Stelzer, and U. Schmidt

Abstract The paper elucidates how to connect forming process simulation with innovative measurement- and analysis equipment thereby taking into account the machine influences. Reverse Engineering use 3D-Scanning data of sheet metal forming dies. Following this paradigm, the models that simulation relies on are refined, and spotting of forming dies is subjected to a scientific analysis. That means, that with Reverse Engineering "extended process engineering" is verified at the real spotting procedure, the comparison of simulation- and measuring results is used to evaluate how close the investigated models are to reality, extending the optimisation algorithms used for springback compensation to die spotting, the modification of the die topology will be carried out automatically thanks to new software functions.

Keywords Reverse engineering · Sheet metal forming · Production engineering

1 Introduction

In efforts to reduce costs in product development while simultaneously guaranteeing the quality of products to be manufactured, the application of virtual methods in product development is becoming more and more important [1].

Requirements for dimensional accuracy in die-formed parts are becoming ever more stringent. Dimensional deviations in die-formed parts mainly result from the calculation models, which until now have not been able to fully and precisely represent the system made up of the die, the die-formed part, and the press in virtual product development. At present, several cycles of manual changes normally have to be run with forming dies. This process is called the incorporation or spotting stage in sheet metal forming. It is performed by die-making specialists who have the ability to integrate fuzzy knowledge and experience.

The manual incorporation step in die-making is opposed to the economic arguments favoring an earlier start to series production and cost reduction. Shortening the length of the incorporation procedure may contribute to overcoming this contradiction. Consequently, the challenge is to adequately safeguard the construction of the die by means of a necessarily qualitatively extended numerical simulation of the forming process to provide reliable forecasts.

This target is achieved as part of a research project whose approach is to virtually calculate a substantial portion of the "rework" that has been necessary up to now in advance, in the die planning or engineering stage, and to make it possible to consider this "rework" during the manufacturing of the die after milling (roughing and finishing) based on the initial design without manual incorporation. As a result, the geometry of the die after milling (roughing and finishing) based on the initial design without manual incorporation should be closer to that of the finished die, that is more near-net-shape. In the future, we may thus reduce the expense and time needed for rework.

2 Target and Methodological Approach

The results of the preceding research projects [2, 3] aimed at FE process simulation have yielded the following findings:

- The model structures and parameterisation options that make it possible to integrate the stretch effects from machine and die cushion into process simulation,
- The information that the stretch (elastic) machine- and die influences that affect the drawing can be simulated ("extended process engineering"),

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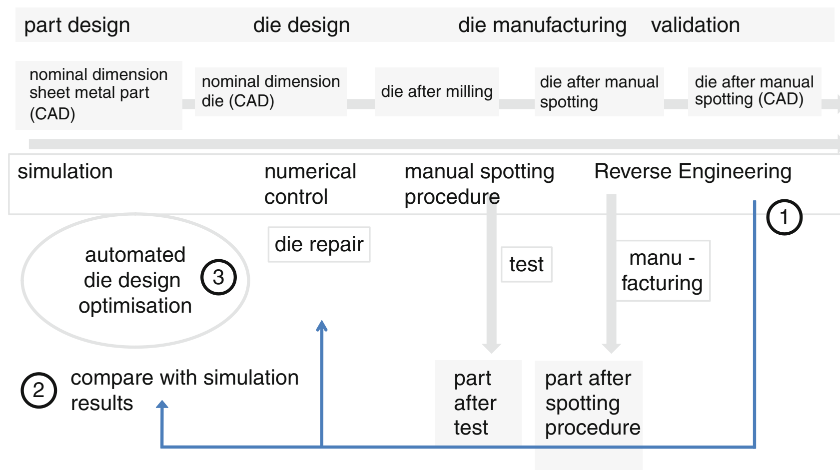


Fig. 1 Planning and execution of forming process, possible effects resulting from the use of CAE methods

- The applicability, in principle, of the extended process model for the virtual modification of the die geometry.

For an application of these elaborated methods suitable for industry, research must concentrate on the following open issues, which are also the main tasks of the solution principle described (Fig. 1):

- Verification of the effect of "extended process engineering" on the real incorporation process by comparing the simulation results with the measured dies and die-formed parts (Fig. 1, point 1).
- Evaluation of the model in terms of how closely it can approximate reality (Fig. 1, point 2).
- Automated adaptation to topology according to die incorporation (spotting) by applying commercially available optimisation algorithms to process – simulation with elastic machine and die influences (Fig. 1, point 3).

The target of the research project consists in linking forming simulation, thereby taking into account machine influences, with innovative measuring- and analysis equipment (Reverse Engineering) [4]. This link is aimed at refining the models used as a basis for simulation and thus creating a scientific background for the incorporation of forming dies and, in turn, providing more efficient die spotting. In other words:

- Reverse Engineering is used as a tool to verify the effect of "extended process engineering" on the real incorporation process, which has not been done up to now.
- Comparing simulation- and measuring results makes it possible to quantify how closely the investigated models approximate reality.

The project work introduced here contributes to shortening the incorporation procedure and thus beginning series production at an earlier date and ultimately saving money. The goal of the project is to calculate the required adaptation of geometry for die incorporation in advance, during process engineering and die design/engineering.

This is made possible by taking into account the effects of the material, machines and tools. Thus, in turn, we create a new basis for the generation of milling data to produce the die after milling (roughing and finishing) based on the initial design without manual incorporation. This way, the geometry of the die after milling (roughing and finishing) based on the initial design without manual incorporation is substantially closer to the geometry of the finished die. Consequently, using the aforementioned methodology and implementing it in practice, the costs and time associated with rework can be reduced.

3 Execution of Experiments

The execution of experiments is oriented towards real world issues relevant to practice and exemplary parts of a particular industrial enterprise. Continuous data recording of the data status of all intermediate die- and die-formed parts over the whole process proved to be a problem. In many cases, for new car models, the earliest stages of development data are subject to stringent confidentiality in terms of special geometric and technological features. We selected a passenger car's back panel. As input data for all geometric comparisons, we have available initially CAD models of the ram, lower die, blankholder and the part to be die-formed. All the other CAD data for the incorporation status are obtained from 3D scanning data.

For 3D scanning, we used the 3D strip projection sensor ATOS-HR produced by GOM mbH [5]. The 3D scanner's accuracy is a function of the used field of dimensions. The scanner has three different measuring fields. For dies and

Fig. 2 Vertical clamping frame with die formed part and 3D-Scanner ATOS

the die-formed-parts we used the middle measuring field with 350 × 350 mm to capture all details of the geometry. For the 350 × 350 measuring field, the manufacturer specifies the accuracy of a single measurement ±0.04 mm. In the case of using this measuring field nearly 20 individual views are necessary. As the investigations showed, in the case of large-sized dies and die-formed parts, it is necessary to record the reference points on the object by photogrammetry in advance to minimise the error when composing the individual views. This way, the photographic measurement and stripe projection we use, incertainty is ±0.04 mm over the whole workpiece. However, without using the photogrammetry, we obtain a measuring incertainty of ±0.500 mm. A vertical clamping frame is used to guarantee a clamping of die-formed parts almost free of distortion (Fig. 2). As result of 3D scanning we get a triangulated point cloud. This data records were used for further work. We also have available the virtual die-formed part geometry with sheet thickness distribution as a result of the forming simulation [6]. The following 3D data records are used for the execution of tests:

1. CAD model lower die after design
2. CAD model ram after design
3. CAD model blankholder after design
4. CAD model die-formed part face after design
5. CAD model die-formed part bottom side after design
6. 3D scanning data lower die after 1st incorporation
7. 3D scanning data ram after 1st incorporation
8. 3D scanning data blankholder after 1st incorporation
9. 3D scanning data die-formed part on top without die incorporation
10. 3D scanning data die-formed part on bottom without die incorporation
11. 3D scanning data die-formed part on top after 1st incorporation and 300 press strokes
12. 3D scanning data die-formed part on bottom after 1st incorporation and 300 press strokes
13. 3D scanning data die-formed part on top after 1st incorporation and 1000 press strokes
14. 3D scanning data die-formed part on bottom after 1st incorporation and 1000 press strokes
15. 3D simulation data die-formed part on top after 1st incorporation and 300 press strokes
16. 3D simulation data die-formed part on bottom after 1st incorporation and 300 press strokes

The numbers of data records 1–16 were used to identify the geometric comparisons.

Due to the comprehensive data material, we have the potential generate a wide variety of comparisons among the data records. The number of possible comparisons N may be calculated with Eq. (1).

$$N = (16^{*}15)/2 = 120 \tag{1}$$

This result indicates that enormous effort would be required to execute all comparisons. Consequently, not all the comparisons are carried out in reality.

In the first step, the CAD models of the dies (data record number 1–3) and die-formed parts (data record number 4,5) were compared with 3D data of different die incorporation states (data record number 6–8) and the associated die-formed parts (data record number 9–14) in terms of geometry. The numerical results for comparison example indicate the geometrical values of manual incorporation versus design data.

Afterwards, the 3D scanning data of the incorporated dies form (Fig. 3) the basis for the modified CAD die models. For this purpose, based on the scans, surface models are generated with Software Geomagic Studio [7]. So we get useful

Fig. 3 Incorporated die (ram) with reference points for photogrammetry and 3D scanning

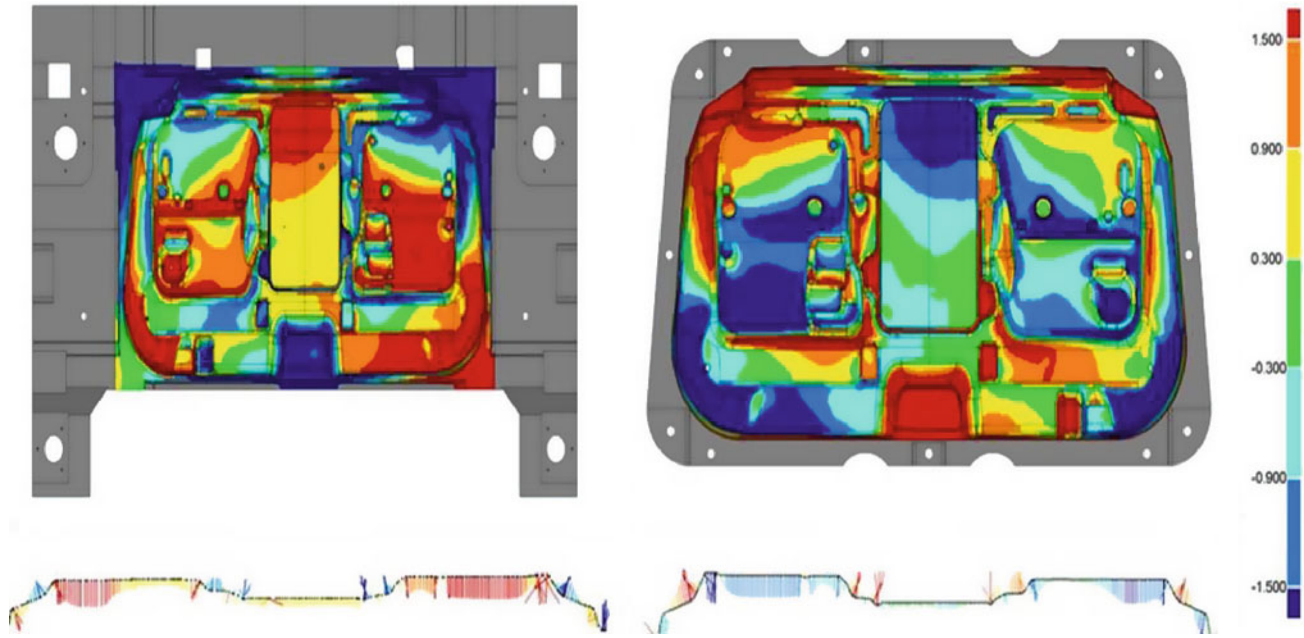
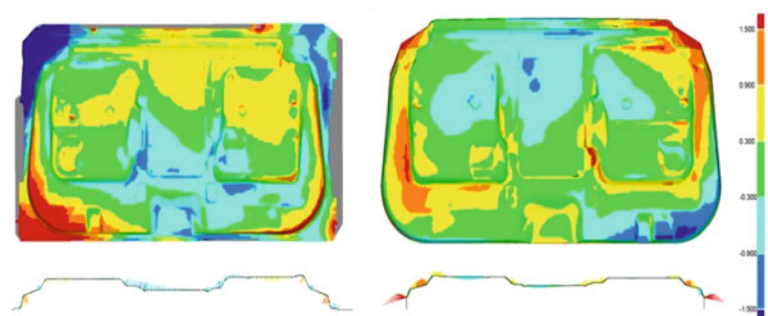


Fig. 4 Comparison of the dies CAD data with the scanning data of the sheet metal obtained form without incorporation, left ram (2 versus 5), right lower die (1 versus 4), deviation in mm

Fig. 5 Comparison of die scanning data after 1st die incorporation stage with scanning data of the parts, die formed after 1st incorporation stage, left ram (7 versus 11), right lower die (6 versus 12), deviation in mm



CAD die models for milling operations. In the next step, the geometries of the die-formed parts and the die are compared per incorporation state. For this task the transformation of the scanned data in the coordinate system of the CAD die models is necessary. This procedure is called registration of scanned data. We used in all cases the best fit registration method. In Fig. 4 the comparisons without incorporation of the die is demonstrated and in Fig. 5 the comparisons of the 1st die incorporation demonstrated. Figure 4 illustrates the deviation between the die surface and the surface of the die formed part (sheet metal) made by this die. During incorporation, the deviations between die surface and part surface are significantly reduced (Fig. 5), since the die geometry is more and more adapted to the normal part geometry.

The geometric deviations can be used to quantify sheet metal springback. In 1st die incorporation the sheet metal springback was reduced. For numerical comparisons of different incorporation states and for comparisons between die-formed part and die, it is necessary to condition the 3D scanning data in the form of triangulated data. If the task is to use 3D scanning data of die-formed parts for forming simulation, they have to be reversed to surface data with Software Geomagic Studio.

To verify the simulation results using the results obtained in reality, we have also to determine the material characteristics of the real sheet metal batches in the laboratory and use them for calculations. In the future, the tests will be enhanced by using real press parameters.

Afterwards, the forming simulation results are also compared with the real sheet metal data. Here, in addition to geometry analysis, we primarily focussed on sheet thickness analysis and its comparison with the measured sheet

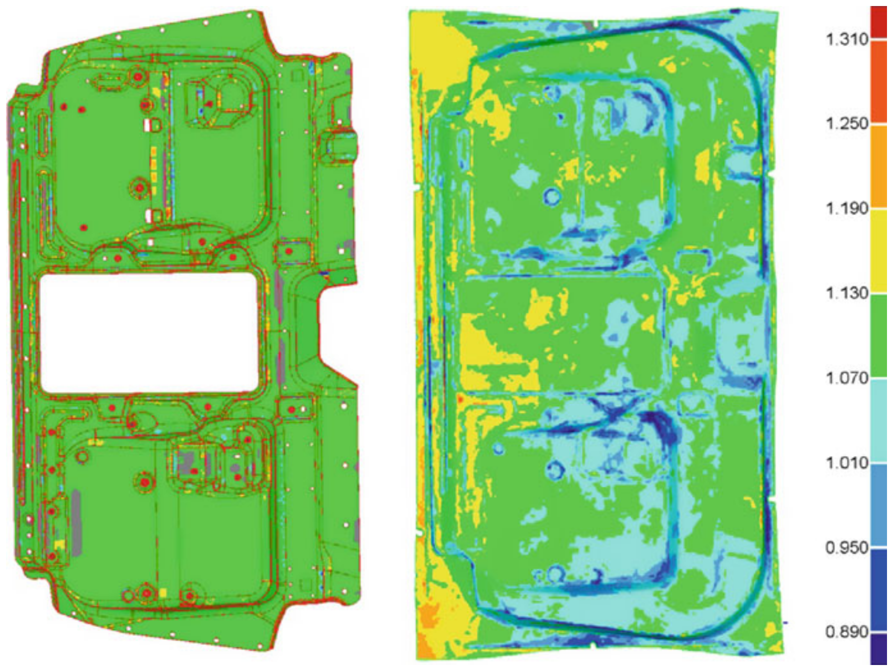


Fig. 6 Analysis of sheet thickness from the die data left: from CAD Data (4 versus 5) and right the parts die-formed after 1st incorporating stage (11 versus 12) in mm

metal thickness values per incorporation state (Fig. 6). We found considerable differences between the theoretical and the real values of the sheet thickness. The real measured sheet thickness was finally used to estimate simulation results.

4 Results

The project is an important contribution to the simulation of forming processes. The project outlines relationships and coherences to determine the model abstractions, constraints and technological parameters required to ensure high process reliability, excellent quality in terms of dimensional accuracy, and reliable reproducibility in the production of formed parts in the planning stage. In "extended process engineering", the following results are sought through consideration of elastic machine- and die influences:

- Modelling for "extended process engineering" according to a methodological approach.
- Creation of a basis of comparison obtained from measurements in the real process to verify and evaluate "extended process engineering".
- Comparative evaluation of the model, thereby clarifying which model is best able to represent the effects of die incorporation.
- Method for automated optimisation of die topology under the impacts of die displacement and – deformation based on commercially available optimisation algorithms.
- Conclusions for an ongoing application of the used photogrammetric measuring technology used, such as for in-process measurement of the die-formed parts or for quality assurance in die-making.

Further investigation of the "extended process engineering" methodology in theory and experiments and its application enables companies to

- Shorten the time necessary to introduce new dies
- Produce forming dies and stampings more economically
- Provide more efficient organisation of maintenance and repair and thus
- Establish themselves as reliable suppliers to their customers who use these dies for their own production in industry

5 Summary

"Extended process engineering" of the real dies and the associated die-formed parts was verified and evaluated in comparison with the geometries obtained using common 3D measuring methods (after milling and after incorporation). To do this, 3D scanning (strip projection method), in combination with photogrammetric measurements to be used for die-making and – incorporation, was modified. In this procedure, the most attention was paid to the instability of the die-formed parts to be measured. A suitable strategy was derived and validated.

For evaluation of the simulation methods, we generate surfaces that can be reversed to CAD. These surfaces are required to

- Determine the TARGET/ACTUAL deviation to initial CAD geometry
- Use the ACTUAL contact geometry for the verifying simulation and
- Comparatively evaluate the simulation results with the real drawing results.

The die topologies measured before and after incorporation were reversed to the forming process models. In the future, the parameters of the associated presses will be involved in "extended process engineering". Thus, it will become possible to evaluate the simulation results to determine to what extent the extended models approximate reality. Finally, the question of which model best approximates the process in reality will be answered.

Further on, optimisation strategies for springback optimisation may then be applied to die incorporation for automated topology optimisation.

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Reverse Engineering of a Piston Using Knowledge Based Reverse Engineering Approach

A. Durupt, S. Remy, and G. Ducellier

Abstract This paper focuses on Reverse Engineering (RE) in mechanical design. RE is an activity which consists in creating a full CAD model from a 3D point cloud. The aim of RE is to enable an activity of redesign in order to improve, repair or update a given mechanical part. Nowadays, CAD models obtained using modern software applications are generally "frozen" because they are sets of triangles of free form surfaces. In such models, there are not functional parameters but only geometric parameters. This paper proposes the KBRE (Knowledge Based Reverse Engineering) methodology which allows managing and fitting manufacturing and/or functional features. In this paper, specific geometric algorithms are described. They allow extracting design intents in a point cloud in order to fit these features.

Keywords Reverse Engineering · CAD model · Knowledge based system

1 Introduction

Reverse engineering is an activity which consists in digitizing a real part in order to create a numerical or virtual model (Fig. 1a). There are many domains related to reverse engineering such as, virtual prototyping, metrology, maintenance of long lifecycle products, tool design, art, entertainment, museology, protection of the industrial patrimony [1, 2] and competitive analysis. This publication proposes, among all these domains, an application of a new reverse engineering methodology that considers redesign purpose. This methodology is called KBRE for Knowledge Based Reverse Engineering and it has been already discussed and presented in several publications such as [3, 4]. A quick summary of the main aspects of this methodology is proposed in the following sections of this publication. This KBRE methodology focuses on the mechanical engineering domain. It exists several reasons to make a reverse engineering operation on a mechanical part: The original design is not supported by sufficient or existing technical documents, the original supplier disappeared or does not manufacture the part anymore and the original part is damaged or broken and no plan nor drawing are available. For all these reasons, considering a redesign purpose is often an issue.

When a redesign purpose is considered, the aim of a reverse engineering operation is to enable a redesign activity in order to improve the geometry of the considered part or to update this one to fit on better manufacturing processes. According to the scientific literature, Reverse Engineering consists in changing a 3D point cloud (obtained using 3D digitizing device) into an accurate geometrical model [5]. Today, according to users, the results obtained using this classical approach is not good enough because the obtained model is generally "frozen" (i.e. a set of free form surfaces or a set of geometrical features in a manifold static model). To enable a redesign activity, a rebuilt model should be like a classical CAD model (i.e. a set of manufacturing and design features with constraints, parameters, rules and relationships).

This publication provides an illustration of the KBRE (Knowledge Based Reverse Engineering) approach that enables people to obtain such a CAD model. The chosen case of study is the reverse engineering of an automobile engine piston.

The first section of this publication presents a quick summary of the KBRE methodology. It consists in a combination between segmentation techniques, feature recognition techniques and a knowledge based approach. Then, the case of study of the piston is considered to demonstrate the efficiency of the KBRE approach. Finally, a conclusion is proposed in order to discuss the advantages, the drawbacks of the

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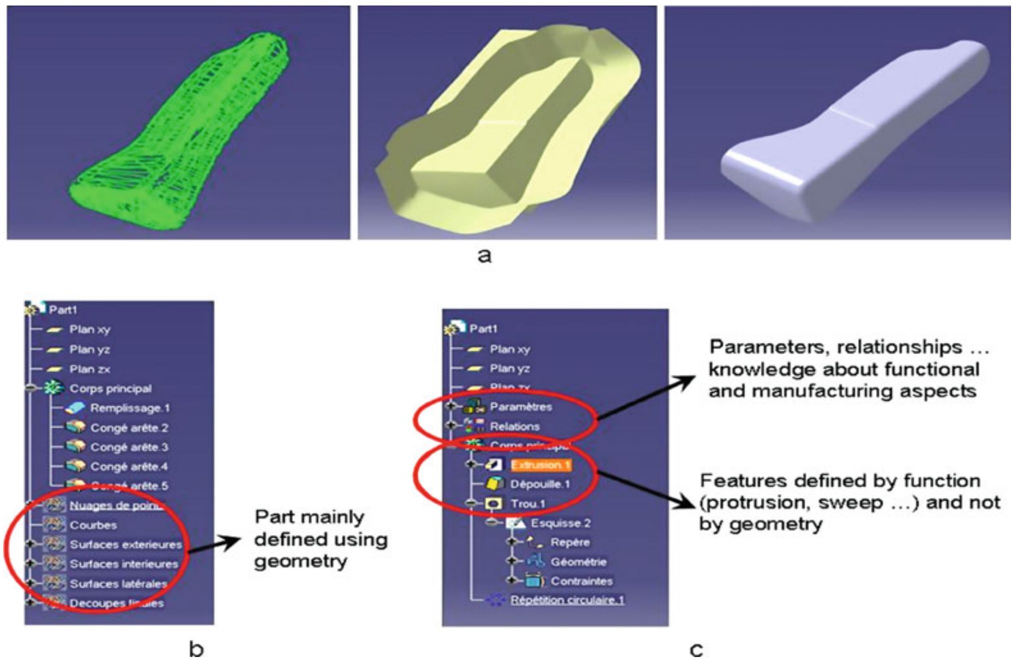

Fig. 1 RE process and different types of model

KBRE approach as well as to propose future works and developments.

2 A Quick Overview of The KBRE Approach

As already said in this publication, the KBRE (Knowledge Based Reverse Engineering) approach as been published and discussed in several publication [3, 4]. In this section, this approach and its main concepts are summarized. It enables understanding the case of study of the piston but also, to understand the differences between this approach and other approaches within the scientific community and those that are implemented in recent efficient tools such as RapidForm™, Geomagic and like. These tools propose powerful algorithms to complete a reverse engineering operation. 3D point cloud segmentation, fitting surfaces and recognition features are very efficient. Surface fitting and feature recognition are accurate and well performed as long as there is a user intervention. In most of the proposed commercial tools, user has to specify the localization of a given feature within the 3D point cloud (using the segmentation) in order to rebuild the geometry of this feature. The KBRE approach aims to reduce user intervention in order to make the RE operation easier. It proposes to use knowledge about the part and its lifecycle in order to improve the feature recognition step after a segmentation operation.

2.1 Segmentation Techniques

The segmentation of a 3D point cloud is an operation that consists in the division of the 3D point cloud of a given object into a set of *n* point clouds representing the *n* features that compose this object. In the reverse engineering process, three segmentation techniques are commonly used.

In a first place, region based technique uses spatial coherence of the data to organize the mesh into meaningful groups [6, 7]. According to this technique, an adjacent region to a given region is absorbed if it satisfies the estimate by the polynomial surface of a given minimal order. If this adjacent region is not absorbed, the smoothing by a polynomial of superior degree is tried. The process stops when all regions are absorbed or when estimations with all polynomial degrees have failed. Current computers improve execution speed of polynomial degrees but this technique is sensitive to the noise of the cloud or the mesh. Normal calculations or curvatures are often noised and borderlines are not clearly defined.

In a second place, technique used is the edge-based method that consists in intending to isolate discontinuities in the 3D point cloud. Break areas such as steps and discontinuities of normal and curvature orientation are recognized. Point detection through parallel slicing sections is the simplest method. Sections are approximated by B-Splines [6]. A second technique consists in performing local characteristics [7].

In a third place, Hybird technique, which combines region and edge techniques, is used. For example, Yokoya and Alrashan [8, 9] have performed the calculation of the discontinuities in the cloud. Region techniques are used in order to finalize the segmentation.

All these techniques lead to surface based CAD models which limit possibilities of redesign. However, solutions exist such as the placement by the user of control points of curves [10]. These solutions are useful for complex surfaces such as airfoils but very sensitive to the noise of the point cloud and require accurate point cloud.

2.2 Feature Recognition and Geometric Constraints

Feature recognition can be generally defined as the ability to automatically or interactively identify and group topological entities from a solid model into functionally significant features such as faces, cylindrical holes, slots, pockets, fillets (i.e. extracting features and their parameters from solids models).

In the scientific literature [11–15], features and constraints represent design intents which are the expert knowledge about the product. The extraction of design intents is the key of reverse engineering. Indeed, an automatic geometrical recognition process does not seem appropriate because the extraction of design intents is more than geometric recognition. In the current proposed approaches, the recognition operations are only based on geometrical functions or relationships. The extraction and the management of expert knowledge are not often bundled in these proposed approaches. None of the commercial software tools and scientific approaches is governed by a structure or a methodology integrating the extraction of the expert knowledge.

2.3 Knowledge Needed for Reverse Engineering

As a hypothesis for the KBRE (Knowledge Based Reverse Engineering) approach, reverse engineering has to consider knowledge about the part and its lifecycle. In fact, it seems obvious that the shape of a given part is due to its function but also to the manufacturing processes that have been used to produce this part.

In modern CAD software application, this hypothesis is already implemented. Today, most of the CAD models are feature based (Fig. 1c) instead of geometrical based (Fig. 1b).

Certain types of knowledge allow extraction of geometrical primitives. As an example, the VPERI [16] (Virtual Parts Engineering Research Initiative) project was created by the US Army Research Office. The knowledge of the geometric shape and size is necessary but not sufficient to reproduce the part. Re-engineering and redesign need functional specifications. A design interface is used in order to allow the addition of knowledge in the form of algebraic equations that represent engineering knowledge of the functional behaviour of the components, physical laws that govern the behaviour, spatial arrangement... In the same way, REFAB [11] system uses manufacturing features. Manufacturing knowledge extraction is achieved implicitly by the user. Mohagheh et al. 2006 [17], in a study case of Turbine Blade, propose a Reverse engineering process that uses information from two different sources: The conventional way (which consists in measuring the model) and the review of design aspects. They preliminary suggest to manually detect specific features which are linked to Manufacturing processes, functional requirements and other considerations before to use segmentation and constrained fitting algorithm. Fisher [18] explores "knowledge based" technique to overcome "frozen in" errors on 3D mesh. The underlying theme behind this set of techniques is the exploitation of general knowledge about the considered object. Indeed, he explains that the full automatic reverse engineering process is not possible because the computers are good at data analysis fitting and humans are good at recognizing and classifying patterns. Urbanic et al. [19], about the reverse engineering methodology for rotary components from point cloud data, explain that features have accurate mathematical definitions or specifications for their geometry, and tolerances depending on functional requirements. They also explain that a functional engineering representation is needed, but when current reverse engineering tools are used for design of rotary components, the final model contains a set of surfaces and curves that have no meanings. They conclude that geometrics primitives issued by one or more manufacturing process could be listed with their parameters. For example, in rotary components, the spindle and screw are standard geometry and could be classified in features.

The above references highlight that two types of knowledge are required to enable redesign operation [20, 21]: The manufacturing knowledge and the functional requirements.

The knowledge extraction phase is very similar to the "product identification" phase in the product development cycle. Here, the starting point is not a concept but a real part.

The KBE (Knowledge Based Engineering) approach and the associated tools are used to accelerate design routine but also to manage design knowledge [3–5, 22]. The approach described in this paper is an application of the KBE approach to Reverse Engineering.

KBRE is a methodology for RE that considers a knowledge extraction phase to improve the RE operation by

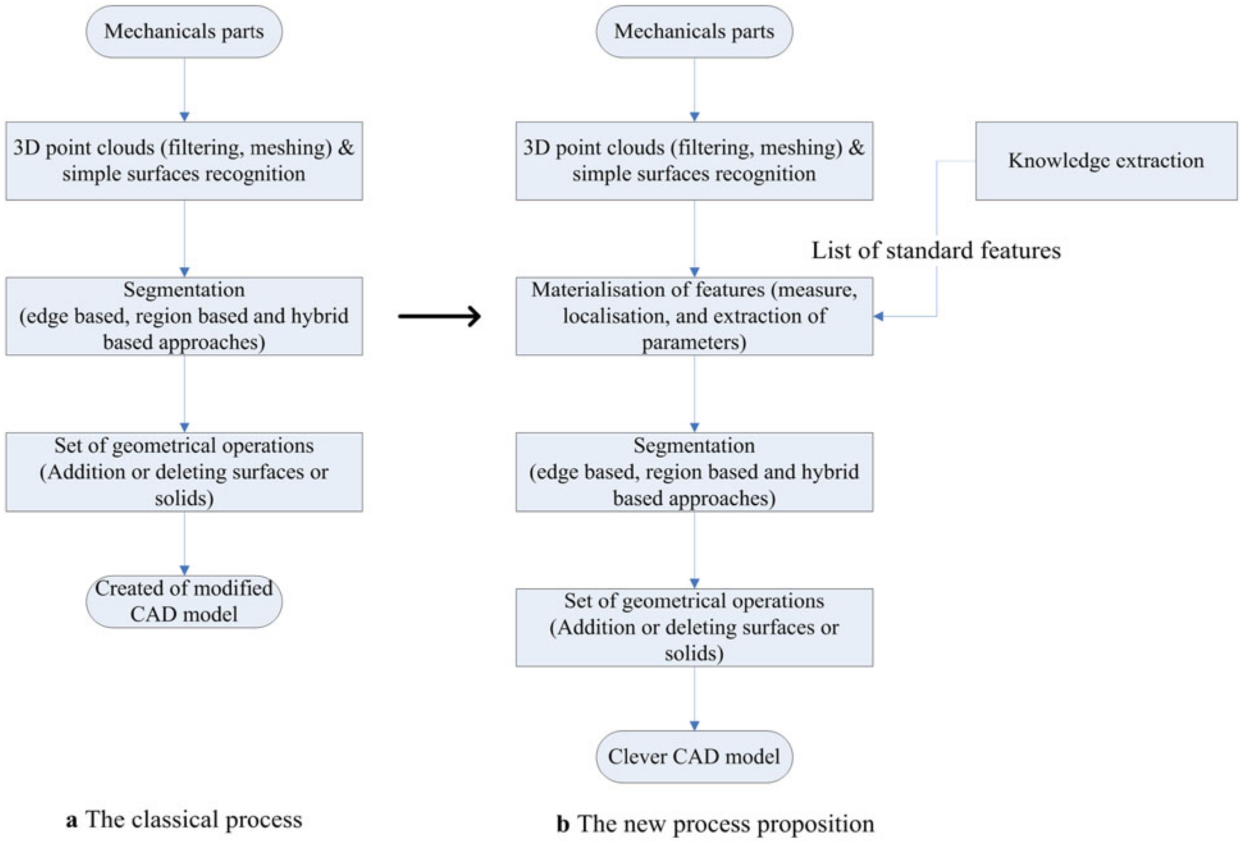

Fig. 2 Classical and KBRE approaches

enabling to obtain a feature based CAD model (Fig. 2). This model aims to be as close as possible to the one that would have been obtained by the original designer using a modern CAD application.

3 Reverse Engineering of an Automobile Engine Piston

3.1 Manufacturing Process Analysis Within the KBRE Approach

The manufacturing process that has been used to create a given part can be found by studying this part. The knowledge of this process can enable to improve a reverse engineering operation. Indeed, mould, casting extraction etc... leave traces on surfaces such as line of joint and draft angle for a mould process. The KBRE (Knowledge Based Reverse Engineering) approach focuses on the manufacturing rules which affect the geometry of the product. For example, considering the forging process, the part has drafts angles. This kind of rule is called "Process-part rule". A database is built using these rules to make them usable in the KBRE tool (Fig. 3). The manufacturing processes are classified according to their types (primary, secondary and tertiary) [23]. The primary class concerns the creating of the form (Moulding, stamping, forging... are concerned). The secondary class is specific to modifying form (milling process is concerned). The tertiary class concerns the enhancing of surface properties, for example (shot peening, laser peening...). For each "process-part rule", one or more theoretical features, called manufacturing features, are referenced in the database. This database already includes the main manufacturing features and it can be customised by any user.

The user can select a referenced feature or add a new one. This manufacturing process analysis contributes to improve a rebuilt CAD model using manufacturing features.

Considering the example of the piston, it is possible to assume that the original piston was manufactured using forging process and specific milling operations. The first process allows extracting the main conical form (body of the piston) and the recess material of the internal of the forging tool. The second process (milling operations) allows boring the internal of the body engine. Three theoretical features can be created and chosen: the "Piston_body", the "Piston_internal_tool" and "Bore". In Fig. 5, all these

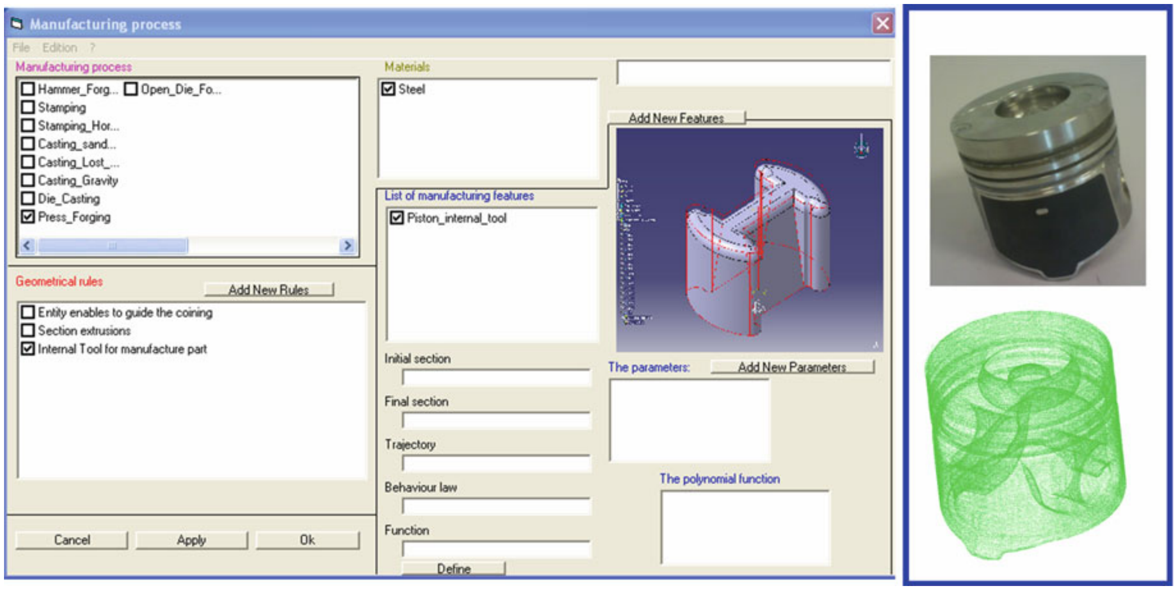

Fig. 3 Manufacturing process analysis

features are illustrated. The next section shows the analysis of the functional requirement of the part.

3.2 *Functional Requirements of the Part Analysis*

A mechanical part, most of the time, has to answer to a need. As hypothesis, a part ensures one or more functions in a given environment (other parts, flow of energy etc.). "Function" and "Environment" terms lead to the concept of functional analysis. Two kinds of environments could be considered:

- "Material elements" such as the surrounding parts.
- "Immaterial elements" such as flow of energy . . .

Consequently, environment of the part is known and can enable explaining the presence of certain features within the part. "Environment" and "interaction" lead to functional analysis. The extraction of the internal and external functions allows revealing specifications of many domains (mechanical, electrical, thermal . . .). The functional analysis enables assuming functional interactions between the considered part and its environment. If the reverse engineering operation concerns just a part, a minimum of environmental knowledge is known. A modified functional analysis form based on the "octopus diagram" is suggested in the KBRE (Knowledge Based Reverse Engineering) methodology (Fig. 4). Indeed, the APTE based graph considers interactions with the studied part and the external environment. In order to structure the approach, each interaction is split into global engineering functions. Each interaction between the part and its environment represents a technical function. Based on the Reverse Engineering experience of the author, seven (7) types of technical functions are considered: (1) the mechanical link (ML); (2) the mechanical structure property (M/S); (3) the electromechanical (EM); (4) the gas/combustion (GC) for thermal properties; (5) the encumbrance (E) for the accessibility; (6) the hydraulic (H) aspects for the hydraulic properties and (7) the specific specification (SpS) for the own view of the user. For each interaction, KBRE suggests design rules where several functional features are referenced. These rules are called "specification rules" and are justified by the nature of the main interaction.

In Fig. 4, a "diagram of octopus" allows showing the reverse engineering of function aspects about the example of the piston. The first step consists in listing the environment part. The connecting rod, the spark plug, the valve and the ring are considered. In the second step, two kinds of interaction are used: The mechanical link (ML.1) and gas/combustion interactions (GC.1, GC.2, GC.3). In the third step, the chosen specification rules concern the context of each interaction. For example, the gas/combustion interaction with the spark club is to enhance combustion of the engine explosion. Thus, in a fourth step, the suggested feature is the "toroid_removal_chamber". The same process is applied for the other interactions. In Fig. 4, an example of KBRE interface shows the functional analysis and the selected features. In the example of the piston, the "toroid_removal_chamber", the "pivot hole", the "circular plan removal" and the "groove" are the theoretical features listed. All these features are illustrated in Fig. 5.

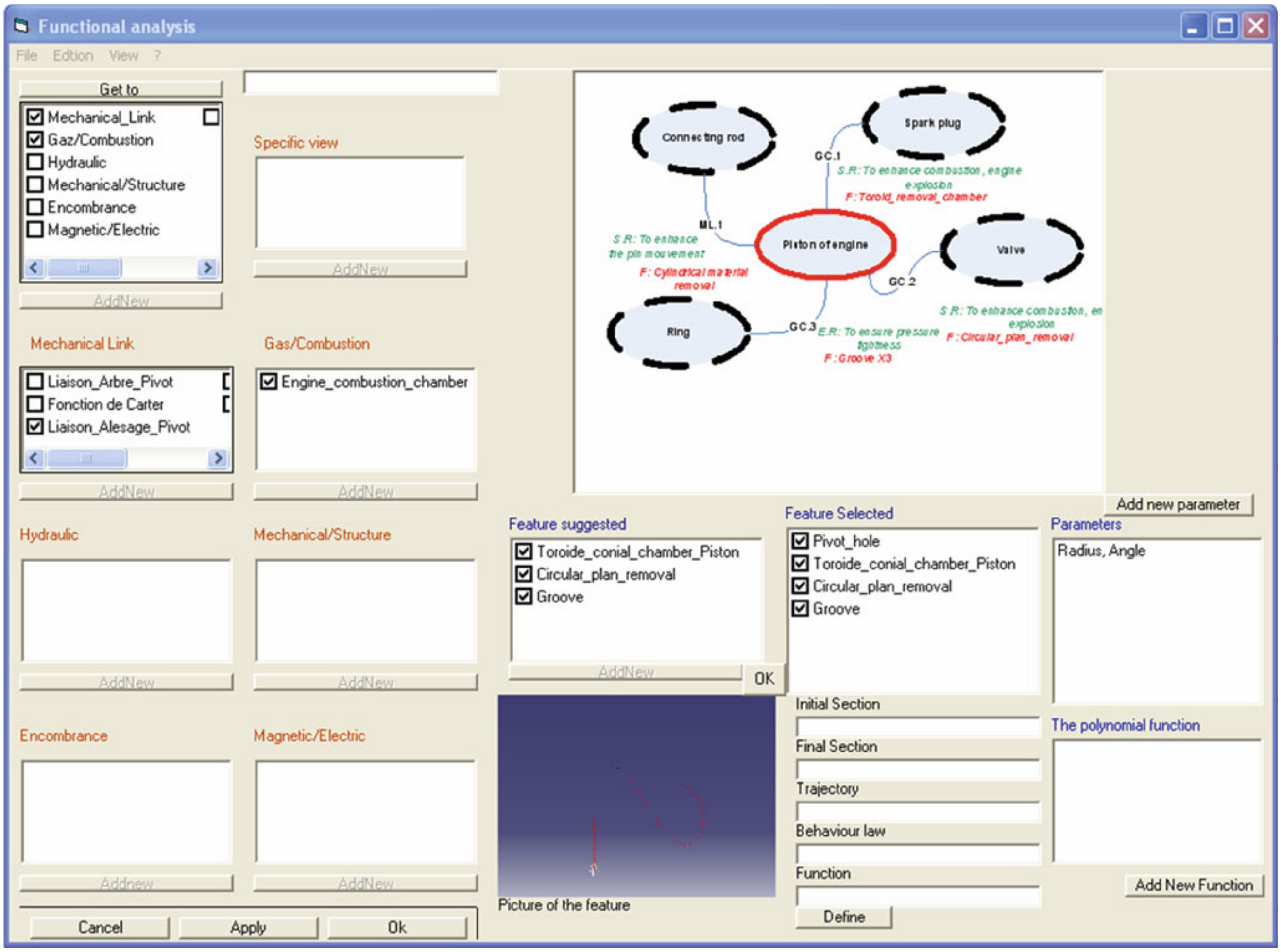

Fig. 4 Functional analysis

3.3 *The Functional and Structural Skeleton of the Part*

The functional and structural skeleton (FSS) of a part is the assembly of the theoretical features that compose this part. Each feature is fitted in the 3D point cloud. In the same way of REFAB, the user clicks on regions (group of points which define one of five primitives: plan, conical, cylindrical, spherical, and toroid) which correspond to the listed features.

The fitting of features is based on the least square approximation. Segmentation is used as a technical support and allows fitting complex features shape. For example, to fit the feature "Piston internal tool", the approximation by a plan is used, the user define three points in a space corresponding to the position of the initial section of the feature. Figure 5 represents a final version of functional and structural skeleton of the piston. The components of each feature are represented by sketches and a function such as extrusion, groove etc which are applied. The obtained CAD model is made of manufacturing and functional features.

4 Conclusion

RE operation based on geometrical approach often provides a frozen and not reusable model. A CAD model cleverer than the resulted geometrical model of current approaches is needed. The aim of this paper is to propose an illustration of a new approach. The KBRE (Knowledge Based Reverse Engineering) approach aims to provide a clever CAD model which can be reintroduce in product development cycle in order to improve the possibilities of redesigning. For this reasons, the proposed approach focuses on the classical design approach adapted to RE issue. This paper defines the features of the part using a manufacturing and a functional point of view. The standard features come from

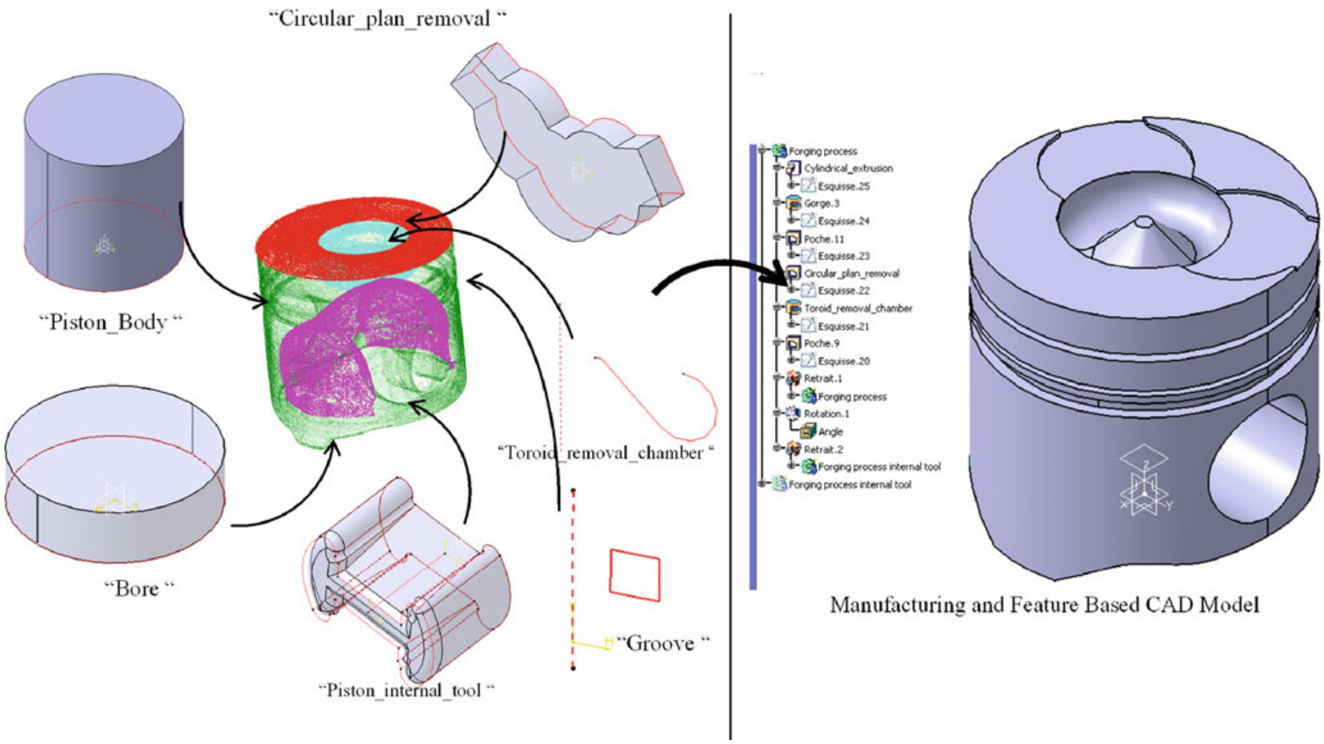

Fig. 5 The functional and structural skeleton of the piston

the manufacturing processes that have been used to make the considered part and from the functional requirements of the considered part. The analysis of the manufacturing processes and functional requirements is required in order to identify the expert knowledge of the studied part. The KBRE approach proposes a methodology which combines a Knowledge Based Engineering approach and geometrical recognition techniques. KBRE allows the redesigning of $2^{1/2}$ prismatic parts for the milling process and casting parts without complex surfaces. In perspectives, KBRE will integrate high performance segmentation techniques and will reference more standard features in the database. The resulting geometries will be built according to the STEP (AP203 2nd Ed.) exchange format in order to export the geometry in other CAD environment.

Finally, this work is part of the PHENIX project (Product history based reverse engineering: towards an integrated expert approach). This project is funded by the French National Research Agency and it aims to develop a software tool in order to combine geometrical recognition and knowledge approach. As the KBRE approach focuses on the reverse engineering of a part, PHENIX deals with a product using a PLM application to manage the data from the knowledge extraction.

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Model Construction Based on CMM and Optical Scanning Data for Reverse Engineering

P.X. Liu and Y. Wang

Abstract This paper introduces a combined modeling method using points acquired by a touch probe on a coordinate measuring machine and an optical scanner. The optical scanning data and the high precision points captured by a touch probe are transformed into a common coordinate system through an improved iterative closet point algorithm. A data merging method is used to keep the high precision of feature surfaces and then unified into a precise 3D model. Experimental results demonstrate the efficiency of the presented method, which enhances the flexibility of digitization while maintaining the accuracy of feature surfaces.

Keywords Reverse engineering · Model construction · Coordinate measuring machine · Optical scanner

1 Introduction

Reverse engineering is a design process going from a physical or clay model to a digital model. It is desirable to generate a complete CAD model that includes all the features and details of the part precisely. The process of reverse engineering normally starts from part digitization and progresses stage by stage through data editing and manipulation, curve and surface fitting, and finally 3D surface or solid model generation. Due to the introduction of rapid digitization technologies and the availability of inexpensive computers, reverse engineering has recently shown a marked increase in implementation. With these, the product design and manufacturing cycle has shown time reduction [1]. Part digitization is the first step in reverse engineering for an existing part, and its precision and efficiency, as well as integrality all will influence the model construction.

Digitization systems can be classified as contact, noncontact. The contact systems, like a coordinate measuring machine (CMM) with a touch probe, which were the most common method for digitizing surfaces in the late 1980s and early 1990s [2]. Today, due to the need for faster cycle times and the development of high speed digitization technologies, their use has declined greatly. Software packages have been developed to automatically move touch probes in a grid like pattern over a surface, however, much effort is still required to set up and monitor the digitization process. The CMM mounted a surface scanning probe greatly improves the efficiency of surface digitization, but still samples at approximately one point per second [3, 4]. If a CAD model exists, offline programming of the CMM is possible by manipulating the CAD model in the graphic display window, which can help to generate a collision-free probe plan. However, for reverse engineering application, the CAD models need to be created by the measured points from the part surface. For all that, the reverse engineering still opens a wide application area for CMMs, when high accuracy (generally in the range of several micron) and availability of, or accesses to, a machine are of primary concern.

The most widespread noncontact system based on optical technologies is much more efficient in terms of speed and reducing the human labour. Just because of this, the optical technology is particularly useful for the reverse engineering process, and a number of systems based on it have been developed. Among them, laser scanners and optical scanning systems are widely used, and both can generate thousands of points in seconds. But these instruments are great inefficiency for precision engineering applications owing to a low accuracy (within the range tens of microns to several hundred microns). Moreover, highly reflective or diffuse part surfaces typically require a coating to allow reliable data collection, which further affects the measuring accuracy. When digitizing a part, users are often faced with a choice, namely, slower, more accurate contact measurement systems or high speed, lower accuracy noncontact measurement systems.

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In the last decade, a large amount of work has been performed to develop methods for the mathematical modeling of optical scanning 3D points, in order to facilitate handling of them on existing CAD/CAM systems [5–7]. There are three major reverse engineering modeling strategies. Automatic freeform surface modeling is the first strategy, which is mainly used for reverse engineering modeling of organic shapes, consumer products such as toys, and medical shapes [1, 8]. In order to facilitate the acquisition of design knowledge and creative ideas for later reuse, feature-based parametric reverse engineering modeling strategy is presented in recent years [6, 9]. This strategy usually need to segment a cleaned mesh or point cloud into function regions, and then surface feature primitives and geometric regularities such as axis, symmetry planes, planar surfaces, quadratic surfaces, extruded and revolved surfaces are recognized and rebuilt. Curve-based surface modeling [10] is the third reverse engineering modeling strategy, in which a 3D model can be reconstructed from scanned data with more precision, since design ideas are usually expressed by outlining the feature curves.

However, no matter which reverse engineering modeling strategy is used, the inaccurate input data will lead to a size approximation of the real feature that can jeopardize the precision of the model. Moreover, each of the digitization methods has several advantages and limitations, and no single method being applicable in all situations. Combining method of data collection in certain cases has the potential of reap significant benefits in process time and data set characteristics, but very few publications have dealt with the issue. Therefore, a combined reverse engineering (RE) modeling method is presented, which based on CMM and optical scanning data, and some key technologies are also discussed.

2 A Combined RE Modeling Method

2.1 The Overview for This Method

The starting point is the acquisition of a number of clouds of points using optical scanner from a part surface, and these points are exported in the form of a triangulated mesh. It is necessary to identify feature surfaces which are measured by a touch probe of a CMM. However, this is a difficult task when no design information for the part is available. Feature surfaces which often include planes, spheres, cylinders and cones usually have tighter tolerances and are designed for some functionality having engineering significance for design and manufacturing processes. The fine finished surfaces or the interface where the part sits all will be treat as potential feature surfaces. These feature surfaces can be scanned quickly by the touch probe and created by the CMM software since they are usually simple algebraic surfaces. For example, a hole only need be touch scanned by a CMM probe in four points to create a bottom plane, two circles, and a closing joint plane for its open end. Then, the feature surfaces and the triangulated mesh are transferred to a CAD software environment for further modelling processes after processing in the data combined system. The data combined system is available for scanned view registration, data reduction, and data merging etc. Figure 1 shows the key processes of the combined modelling method. The presented method does not include the physical integration of two sensors but includes their combination at the measurement information level.

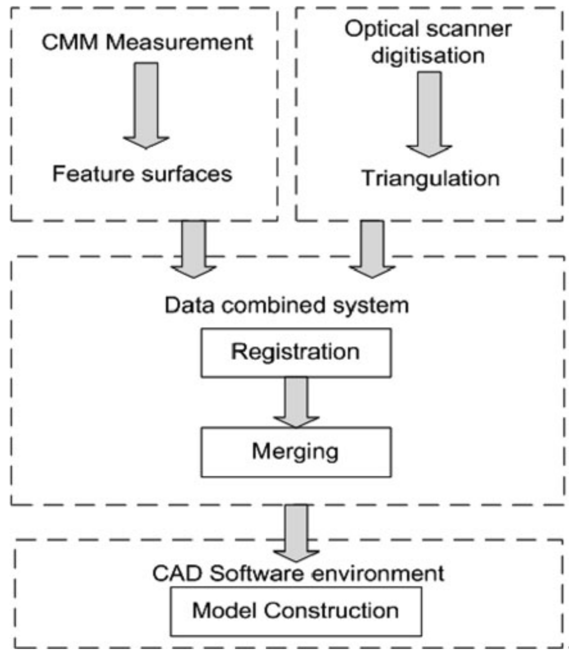

Fig. 1 Model construction based on CMM and optical scanning data

2.2 Registration of CMM and Optical Scanning Data

In a combined method, data collection using a CMM and an optical scanner must be transformed into one common coordinate system. Most research related to registration was focused on multiple optical scanned views. However, the resolution of data from CMM and optical scanning is different, no corresponding points or geometric intrinsic. The use of prismatic datum artifacts is popular for both type of data set combination, or registration, but the process is not flexible and the precision of registration completely depends on the measuring accuracy of these artifacts. In fact, the uncertainty in this process lies in determining the location and orientation of the artifact, relative to the part, for each data set. Therefore, an automated registration method is presented, in which primitive artifacts are not required as datum.

Three points will determine a coordinate system in mathematical sense. Consider two matched point sets $\{p_i\}$ and $\{q_i\}$, $I = 1,\ldots,3$, they can transform into a common coordinate system by the orientation matrix in Eq. (1)

$$p_i = \boldsymbol{R}q_i + \boldsymbol{T} \quad (1)$$

where $\boldsymbol{R}$ is a 3×3 rotation matrix and $\boldsymbol{T}$ is a 3×1 translation matrix. Let the position vector from point p_1 to p_2 be $\boldsymbol{v}_{21}$ and that from point p_2 to p_3 be $\boldsymbol{v}_{23}$. Point p_2 is set as the origin. The vector $\boldsymbol{v}_{23}$ is set as the X-axis and the cross-product of $\boldsymbol{v}_{23}$ and $\boldsymbol{v}_{21}$ is set as the Z-axis, and then the cross-product of X-axis and Z-axis is set as the Y-axis. Thus, the orthogonal frame {X, Y, Z} can be assigned. Similarly, the orthogonal frame $\{X', Y', Z'\}$ can be assigned using the point set $\{q_i\}$. The rotation matrix and translation matrix can be calculation by finding the relationship of the above two frames. The primary problem with this algorithm is that the accuracy of the transformation is affected by the measurement error on each of the above three points. Fortunately, it need not how accuracy results in the process of the initial registration, as long as select three points corresponding approximately from CMM and optical scanning data respectively.

The conventional iterative closest point (ICP) algorithm [11] is the one of the most popular registration techniques. It is realized by iteratively searching for the minimum square distance of the closest sets of points on a geometric entity to another set of given points. This method requires, for example 200 points in the common area in each merging view to result in successful registration. Obviously, there is no such corresponding relationship. Instead of direct searching for the closest point, an improved iterative closest point method based on projection is adopted for the fine registration.

A triangle mesh structure is used to interpolate the input point clouds from an optical scanner. Define the triangle vertices set $\{\boldsymbol{v}_j\}, j = 1, \ldots, m$ where m is the number of vertices. Define the point set $\{\boldsymbol{d}_i\}, i = 1, \ldots, n$ where n is the point number, sampled from feature surfaces by a touch probe. The fine registration process is based on the calculation of distances from the point set $\{\boldsymbol{d}_i\}$ to its neighbouring triangulated mesh. In order to improve the speed of the algorithm, the *k-d* tree is used, and its output is the vertex $\boldsymbol{v}_i$, which is the closest to the data point $\boldsymbol{d}_i$, as shown in Fig. 2. Given $\boldsymbol{d}_i$ the closest point $\boldsymbol{m}_i$ will lie within or on the border of, one of the triangles to which the vertex $\boldsymbol{v}_i$ belongs. It is necessary to project $\boldsymbol{d}_i$ into the planes defined by each of these triangles to find the point $\boldsymbol{m}_i$. The resulting projected points will either lie inside or outside of a given triangle. For each triangle, if the projected point lies inside the triangle, define $\boldsymbol{c}_l$ as this point,

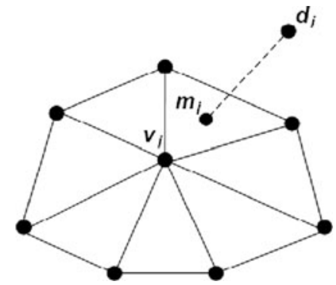

Fig. 2 The finding of the closest surface point $\boldsymbol{m}_i$

where l is the triangle index. If the projected point which lies outside of the triangle, $\boldsymbol{c}_l$ is defined as the closest point on the border of the triangle l to the projected point. Finally, $\boldsymbol{m}_i$ is found as the point which is closest $\boldsymbol{d}_i$ to among all $\boldsymbol{c}_l$. The transformation matrix computed by applying the ICP on the both point sets of $\{\boldsymbol{d}_i\}$ and $\{\boldsymbol{m}_i\}$ is used to transfer the feature surfaces to be best aligned with mesh model.

Note that the triangle to which the point belongs will be assigned a label updated at each iteration, in order to recorder the potential overlap region of the feature surfaces and the triangular mesh model.

3 Data Merging

When the registration has been performed, the CMM scanned data overlaps with the triangular mesh model. It needs to remove the redundant mesh in the overlapping region. The elimination is based on the feature surfaces measured by the CMM touch probe. Mesh segmentation is a necessary process of separating the triangular mesh into groups corresponding to feature surfaces.

A step segmentation method for mesh is employed. The mean shift algorithm which is a nonparametric clustering technique is extended to normal filtering to increase robustness of the method. Triangle normals $\{\boldsymbol{n}_i\}$ are considered as scattered data $\chi = \{X_i = \boldsymbol{n}_i | \boldsymbol{n}_i \in \mathrm{N}\}$ in R^3. It is convenient to use mean shift procedure [12]. This study used the topology information of the triangular mesh for the accelerating query process. The step of this algorithm is described below.

1. Let $\boldsymbol{v}_i (i = 1, 2, 3)$ be vertices of a triangle t and $N_t(V_i)$ is the 1-ring adjacent triangles of $\boldsymbol{v}_i$. Then defined $N_t = N_t(v_1) \cap N_t(v_2) \cap N_t(v_3)$, and N_t is the nearest neighbours of t for query.
2. For each triangle equipped the normal $\boldsymbol{n}_i$, check whether its normal counterpart n_j which is the triangle normal in N_t satisfies $\| \; n_i - n_j \; \| < h_n$. Apply mean shift procedure to obtain the mode denoted by $\boldsymbol{n}_m$.
3. Update the normal $\boldsymbol{n}_i$ equal to $\boldsymbol{n}_m$.

Here, h_n is the bandwidth by user setting. After mean shift filtering, the noises remove in triangle normal while preserving the features.

Once the mesh normals are prefiltered with mean shift, triangles are classified according to their normals. The clustering is done via a k-means algorithm, a fast least-squares partitioning method which allowing to divide triangles into k-groups, namely each triangle is associated to a cluster C_i i=1,...,k. Then a region growing process is performed to recovering the region consisted of triangles with same label.

The region merging is a necessary step for reducing the over segmentation and identify algebraic surface. Curvedness which is known as the bending energy measures the intensity of the surface curvature and describes how gently or strongly curved a surface is. Mathematically, it is defined as

$$C_V = \sqrt{(k_{\max}^2(v) + k_{\min}^2(v))/2} \tag{2}$$

where $k_{\max}(v)$ and $k_{\min}(v)$ are the principal curvatures of the surface at vertex v and are estimated by the algorithm [13].

To merge adjacent similar regions, a region adjacency graph (RAG) is constructed in which each node represents a connected subset of the mesh and each edge represents an adjacency between two regions. Edges are evaluated by a similarity distance dc_{ij}, computed as

$$dc_{ij} = \| c_i - c_{ij} \| + \| c_j - c_{ij} \| \tag{3}$$

where c_i and c_j are the average curvedness (not include boundary vertices of region) corresponding two adjacency region, and c_{ij} is the average curvedness of their boundary vertices. The merging of the graph is processed: the smallest edge of the graph is eliminated at each iteration, thus the corresponding regions are merged; then update the graph. When the weight of the smallest edge is larger than a given threshold, this graph reduction ends.

After the segmentation, each triangle is assigned to a patch. The patches to which the triangles in potential overlap region belong are regarded as the region corresponding with CMM scanned features and will be wiped out from the mesh model and replaced by CMM scanned features. In the final stage the merging data including CMM scanned features and the mesh model will output into CAD software environment for the 3D model construction.

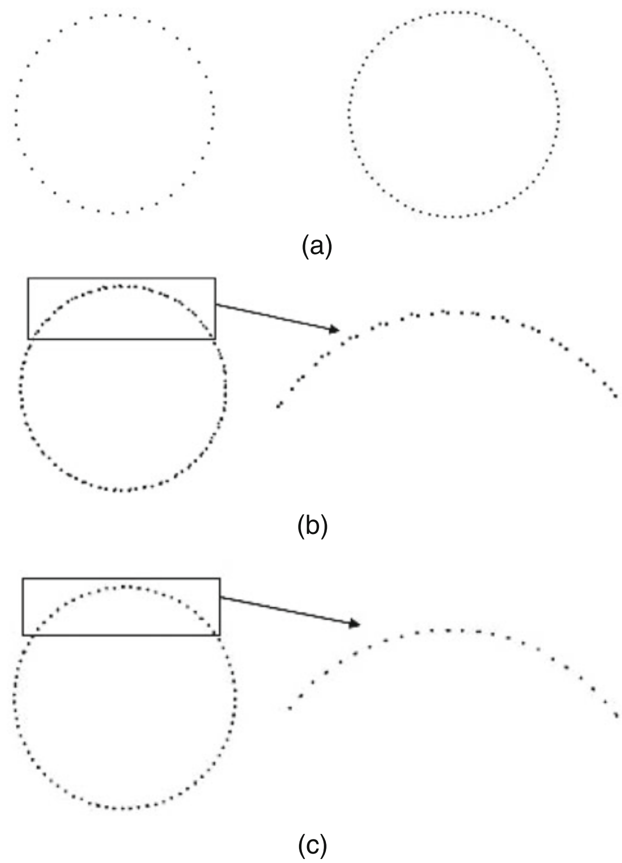

Fig. 3 Comparison between ICP and improved ICP

4 Results and Discussion

The comparison of the traditional ICP algorithm and the improved ICP algorithm is shown in Fig. 3, and all the views are the top view. The sampled data of cylinder is used to simulate the data acquired by CMM (sparse data at left) and optical scanner (dense data at right), as shown in Fig. 3a. Figure 3b shows the registration view using the traditional ICP. Figure 3c shows the registration view using the improved ICP. From the comparison presented in Fig. 3b, c it is observed that the improved ICP exhibits strong advantage for the registration of the data with different density.

The noise contaminated in the data may come from digitization and form error. Figure 4 shows the segmentation results of a noise corrector. The noises are introduced by post wear, as shown in Fig. 4a. Figure 4b shows the segmentation without mean shift. Figure 4c presents the segmentation with mean shift. Through the comparison presented in above two figures, the normal filtering with mean shift can effectively deal with the noise, thereby resulting in robust segmentation. The last segmentation result after region merging is shown in Fig. 4d.

Figure 5 shows the process of the combined RE modeling method applied to a casting. A touch probe on a CMM with an accuracy of 0.6 and a five-axis optical scanner with an accuracy of 15 are used for digitizing this part. The triangle mesh interpolated from optical scanning data is shown in Fig. 5b. The actual features of casting surfaces

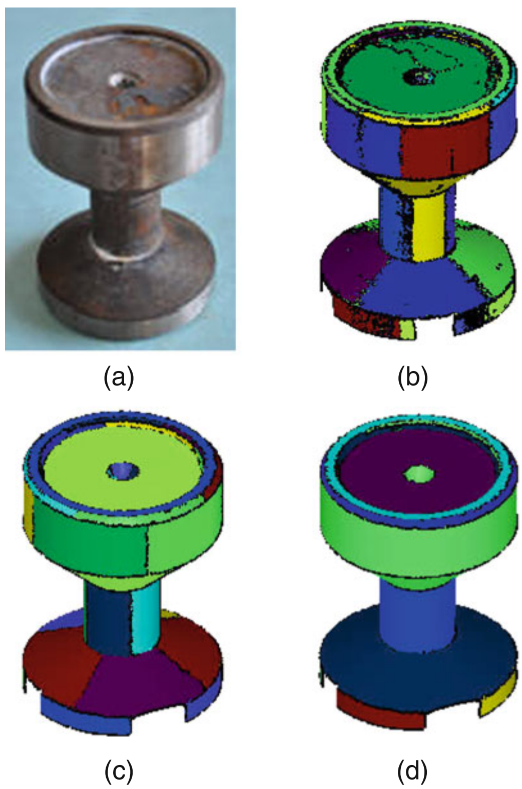

Fig. 4 The segmentation results of a noise corrector

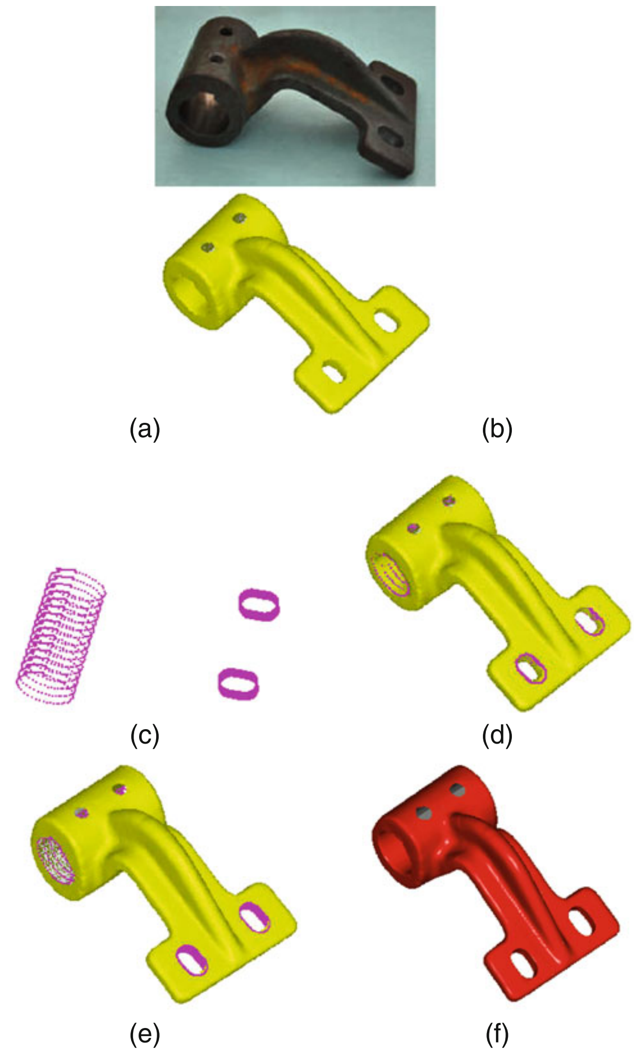

Fig. 5 Reverse engineering of a casting by the combined RE modeling method

are not required for machining purposes nor are those features accurate. However, the exact models of machined holes are required. Therefore, the critical feature holes are scanned using a CMM touch probe, as shown in Fig. 5c. The distance between these features are also extracted from the CMM stage, which are crucial in the process of remanufacturing. The results of registration and merging are shown in Fig. 5d, e, respectively. Finally, the 3D model is constructed at the CAD software environment, as shown in Fig. 5f.

5 Summary

This paper presents a novel method for 3D shape construction based on CMM and optical scanning data for reverse engineering. It is the combination at measurement information level. The experiment results indicate that this method particularly adapts to the RE of the part that have complex geometry surface but low accuracy need and several standard and precise machined features like some automotive and aerospace casting components. As part of future work, a plan is to focus on fasting modeling by employing more automation in the system processes.

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Virtual-Reality-Based Simulation of NC Programs for Milling Machines

R. Neugebauer, P. Klimant, and V. Wittstock

Abstract This paper addresses Virtual Reality-assisted pre-testing of NC programs and describes the benefits of testing them with respect to processing on the NC control unit. Thereby collisions of machine axes can be recognized, downtimes can be minimized and costs arising from faulty NC programs can be cut. Newly-engineered visualization of material removal in real-time-capable VR systems facilitates an even more realistic simulation of the production process, and thereby enables even those users who are not specialists in the field to quickly comprehend the ever more complex processes involved, and thus to recognize potential errors more effectively. By using the hardware in loop-coupling between a real NC control unit and a virtual machine model, errors caused by the NC control unit itself can be recognized.

Keywords CNC Simulation · Virtual reality · Hardware in the loop · NC programs

1 Introduction

Currently, Virtual Reality (VR) technologies are finding an increasing number of applications in modern mechanical engineering. However, they are still a long way from being fully integrated into the entire product development process. Numerous companies are reluctant to make the necessary investments for the VR basic equipment. Yet, the fact that implementing VR technologies can reduce engineering costs (particularly the cost generated by failures and rejects) is usually not taken into acCountryt in making such decisions [1].

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Increasingly affordable hardware prices and more fully developed VR software tools create two benefits: a reduction of the amortization period and the capacity to implement more functionality. Well-founded expertise on VR engineering remains a basic requirement for working successfully with VR. Today, numerous research centers are engaged in the further development of existing interaction devices and techniques. Their primary objective is to make these technological innovations easier to use.

Despite new interaction devices and a more user-friendly manner of operation, many potential users still feel a sense of inhibition when it comes to VR technology. The goal within the coming years is to break down this barrier by means of improved integration into the product development process and simplify end user applications, in order to be able to tab the full potential of this technology.

The use of VR has already become established, particularly in dealing with issues which can only be handled interdisciplinary. Some examples include: Design Review, FMEA, and ergonomic considerations in the typical virtual environment, as well as the orientation and training of employees in a virtual environment [2].

The aim of the research project described in this paper is the expansion of the existing broad spectrum of VR technologies in the mechanical engineering sector by means of virtual commissioning. To achieve this goal, a real Siemens tool-machine control unit was coupled with a virtual model of a 5-axis milling machine. This so-called Hardware in the Loop (HiL) coupling enables two advances: the use of the complete array of functions in the NC control unit, along with the facilitation of diverse pre-production tests using a virtual machine model even prior to production on the actual machine. These advances enable thorough and affordable testing of the virtual prototype.

This type of simulation offers the user the possibility of testing the functionality of a machine. In addition, this Hardware in the Loop coupling is also very well suited for employee training. It permits employees to test (in advance and without risk) the machine's response in the event of an error. Well-trained employees will subsequently cause fewer

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errors; this, in turn, reduces the error rate along with the costs associated with errors and downtime for the actual machine. Furthermore, this enables the machine's manufacturer to detect errors and correct them – even prior to the completion of the first prototype.

2 Virtual Reality Based Simulation

2.1 From CAD to Final Product

Today, new products are developed based on 3D-CAD models – no matter if they have complicated geometries, such as an automobile body, or if they are standard parts, such as gears. Designers generate all models in 3D using CAD programs. The 3D-CAD data generated in this manner offers numerous advantages in comparison to the classic method of design on the drawing board. Using a realistic illustration of each individual part, designers can recognize problems that occur at an early stage and remedy them. A realistic VR-aided visualization of design data on a scale of 1:1 also offers outside observers the chance to recognize errors and give feedback to the designer. Its use is particularly effective in the context of an FMEA (Failure Mode and Effect Analysis), in which specialists from diverse disciplines assess the CAD models. Previous experience[1] has shown that VR-aided FMEA can detect many more sources of error than the classic method.

Once the design of the CAD model is completed, the machine tool on which the work piece will be produced must be prepared for production. This process includes elements such as the selection of a suitable work process (turning, milling. . .), the selection of the necessary tools, and painstaking planning of the individual steps involved in this work. For this purpose, so-called CAM (Computer Aided Manufacturing) programs are used.

The use of CAM tools supplants the classic method by which design drawings with instructions and guidelines were handed over to the production staff, which then manually generated the NC programs. Nowadays, all production-relevant data flows directly from the CAM programs to the NC control units [3].

The complete NC program generated by the CAM software is constructed according to the specifications set forth in DIN 66025 and/or ISO 6983. These norms ensure that all conforming NC programs can be run on any NC control unit.

Competing manufacturers of control units have devised internal standards that deviate from these norms; such firm-specific specifications require an interim process step before it is possible to run the NC code generated by the CAM program on the NC control unit. For converting the NC programs, control unit manufacturers provide their own post-processors. The post-processor additionally enables the use of ready-made subprograms for specific production processes (such as the milling of pockets), which increase the speed and especially the precision of work compared to the NC standard. Following a successful post-processor run, the NC program is transferred to the control unit [4].

Once this has taken place, the machine tool must be prepared for the production of the work piece. This step takes place based on the flow chart generated in the CAM environment. This means, for instance, that all tools must be placed in the tool changer's magazine, measured in advance, and also entered in the NC control unit. Furthermore, the work piece must be clamped in the previously-designed fixture. Finally, by 'lightly scratching the surface' of the work piece, the machine determines its exact position in relation to the machine coordinate system. This is essential, since the NC program uses the work piece coordinate system as a reference, and the machine tool performs (for the NC program cycle) a coordinate transformation from the work piece coordinate system to the machine coordinate system. This inverse transformation must be performed for each item [3].

Once these requirements are met, the work on the first work piece can begin. A so-called 'test run' is performed at significantly reduced feeder speed to correct the remaining errors in the NC program. In this process, the intention is to verify the following elements, among others: errors in the NC program and path points that the machine cannot reach, and individual collisions between the machine tool axes.

Commissioning of the machine tool can take a very long time, and also may produce several work pieces as rejects while causing a great deal of wear on the tool.

2.2 NC Program Verification

In principle, automatically generated NC programs may be run on the NC control unit without prior testing. Frequently, however, these programs have considerable potential for optimization; for example, shorter travel paths for the individual axes, fewer downtime intervals and optimized milling strategies. In addition, these programs may even contain errors. For instance, if the inputs previously made in the NC program do not fully match the actual tools, collisions can result. Additional sources of possible error are path points included in the NC program that the machine cannot implement due to structural factors; this condition, in turn, results in an immediate stoppage in processing prompted by the NC

[1] Implementation of VR-aided FMEA and Design Review on the premises of mid-sized German companies.

program. Correcting these errors and optimizing the automatically generated NC program requires significant expenditures of time and resources on the actual machine tool.

The use of a virtual machine tool model (in combination with real machine controls) makes it possible to optimize the NC program prior to its first run on the actual machine, and to correct any errors it may contain [5].

Applying virtual machine models in association with actual machine tool controls contributes significantly to the conservation of resources and energy. Thus, during the test phase, the machine can continue to produce parts belonging to the previous batch, substantially reducing downtime periods for the machine tool. Additional benefits and possible applications of virtual machine models in the design of new machines include: digital design space testing, parallel electrical design, setup and configuration of the NC control units, and the ability to test the NC program even before a physical prototype of the machine is available.

2.3 Simulation Tools – Desktop vs. Virtual Reality

Most programs, which are developed for testing automatically generated NC programs, are desktop-based and divided into two parts, a machine and a control unit. If the NC control unit is available as a program on the simulation computer, it is known as Software in the Loop (SiL) coupling. These simulation programs map the workspace of the machine tool, permitting verification of such elements as speed, the tool's movement paths and the precision of the geometry of the work piece to be produced. The software that is mapped by the NC control unit also responds to errors. An example for a desktop-based simulation program is VERICUT from CGTech [6]. The VERICUT module CNC Machine Simulation allows testing the movement of the machine axis, as well as the material removal at the work piece. Throughout the usage of the G-Code, testing after the post-processor is also feasible. To provide the G-Codes functionality, VERICUT uses own libraries to decode the G-Code from the most established NC control units.

However, simulations can only reflect selected aspects of an entire system. Those NC control units that have evolved significantly in the last few years (and, as is typical in automation engineering, work internally in real time) are especially difficult to map in their complete functional scope [7].

For this reason, in the last several years, another type of simulation has been established. Hardware in the Loop coupling uses the actual NC control unit and maps the machine tool as a virtual model. In this context, the greatest challenge is coupling the NC control units to the virtual model, since NC control units, as described above, work in real time and, as a consequence, the response from the simulation program must take place within a certain time interval [5].

In this process, the depth of the simulation program plays a decisive role. If the movement paths of the machine are to be optimized and tested for collision, connecting the control unit is relatively simple. However, if the machine's individual actuators are also to be mapped (primarily with regard to their masses and inertia ratings), this type of model formation proves to be quite difficult, since most actuator models use complex and abstract simulation models of the kind generated, for instance, with Matlab Simulink. With the aid of such models, individual actuator parameters can be verified and mapped quite effectively, but their high degree of abstraction complicates testing for collisions between the machine's axes. Since the requirements imposed by this coupling of the control unit are so extensive, the NC control unit is usually only operated in what is known as 'simulation mode'. In simulation mode, the outgoing target values are returned directly as actual values to the internal position regulator (for the closed loop position controller). With this kind of HiL coupling (which does not operate in real time), the NC control unit runs the NC program as usual, and the connected virtual machine model proceeds exactly according to its specifications. This enables early testing of the NC program and the detection of possible collisions between machine axes. The drawback of this variation is that the control unit's internal regulatory structures cannot be tested simultaneously.

Other possible errors caused by the NC control unit, such as reaching a point outside the machine's work area or possible collisions between the machine's axes, can thus be recognized and corrected. Potential consequences of these types of errors can range from a 'Stop' on the NC control unit to severe collisions that may even lead to the destruction of the machine.

Because it uses the actual control unit, this type of coupling is ideally suited to the optimization of movement paths and the reduction of possible downtime intervals. Also, the correct configuration of the tool parameters on the control unit can be verified at the same time.

Due to the significantly more realistic function of HiL as opposed to SiL coupling, this process is better suited to the virtual commissioning of a machine tool.

3 Hardware in the Loop Coupling of a Virtual Machine Tool with a Real CNC Control Unit

3.1 Preparation of the CNC Control Unit

To establish an effective HiL coupling between a virtual model and a real control unit, some adjustments must be made. Also, the necessary machine parameters (such as limit switches and the number of axes) must be defined, and tool lists must be created [8].

There are two possible ways to connect the model to the control unit. One variant is the use of a proprietary automation bus. Another variant is to read out the axis specifications directly from the control unit and send them via Ethernet (TCP/IP). In the second variant, a thorough and precise familiarity with the structure and function of the control unit is required. Also, the manufacturer must release this option in advance (Fig. 1).

A direct readout of the axis specifications from the NC control unit is possible, since the NC control unit sends all current axis values in parallel to its Human Machine Interface (HMI). This process employs the internal Windows Service Dynamic Data Exchange (DDE), which also enables transmission of the data to any other computer in the network. Then, these axis values must be entered into the virtual machine model.

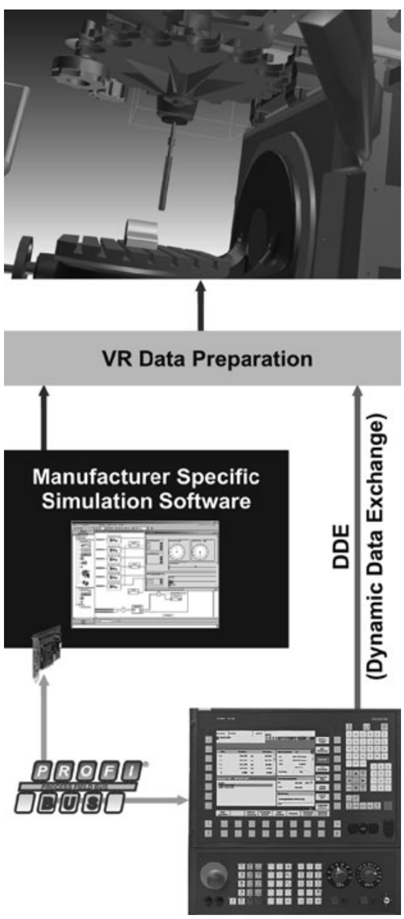

Fig. 1 The two interfaces for receiving the axis values from the control unit

Coupling via the manufacturer-specific Profibus-DP[2] the actuator bus requires a computer equipped with a specific Profibus PCI card, since this connection entails specific requirements. The hardware configuration in the NC control unit must be adapted to enable the configuration of the new Profibus device on the control unit. This process, in turn, requires several modifications in the control unit system, which must then be undone in the course of actual implementation. Although the extensive effort involved in configuring the NC control unit is a drawback of this variant, its benefit lies in providing a real-time connection between the Profibus-DP PCI card and the NC control unit. As described earlier, no real-time connection is available with the DDE connection. Therefore, for a subsequent actuation simulation or for a simulation of the moving masses (multi-body system – MBS), the Profibus-DP coupling should be used. However, most of the errors in the NC program can be detected via simulation of the movement paths with the corresponding movements of the machine tool axes. Here, the NC control unit works in simulation mode; that is to say, the internal position regulator immediately applies its target axis specifications as actual axis values. That means that no deviations in shape or position due to moving masses are included for consideration.

For a Profibus-DP coupling, an additional software program is required to decode the coded axis values sent via the Profibus and forward these along to the VR system. Examples of such manufacturer-specific software programs include the SINUMERIK Machine Simulator by Siemens and the Indraworks Machine Simulator by Bosch. In principle, these programs offer the option to assume direct control over the NC control units. However, these functionalities are limited to simple binary signals, since, on the one hand, the generation (and above all, the calculation) of MBS (Multi-Body Simulation) systems requires a great deal of effort and, on the other hand, real-time requests by the control unit must be fulfilled. Real-time requests, however, can only be fulfilled after all calculations within the corresponding bus cycle of the NC control unit have been carried out. The visualization options furnished with these two software solutions merely include movements of the individual axes without simulating the material removal on the work piece.

As a result, the DDE connection is more suitable for visualization of the machine's movements, since for this process, no modifications must be made to the NC control unit [10].

[2] Profibus (Process Field Bus) is a standard for field bus communication in automation technology (for further information about Profibus see e.g. [9]); DP stands for Decentralized Peripherals.

3.2 Virtual Machine Model

CAD data from the machine tool provides the starting point for a virtual machine model. The complete CAD data record contains a very large number of polygons. To enable the VR system to effectively transfer such large quantities of data, the machine must be optimized in an initial step for this process. Here, the first priority is to hide all parts not immediately relevant to the simulation, such as setup elements, the machine's casing, peripheral actuators, etc. This step must be performed manually by the operator, yet when performed correctly, reduces the number of polygons in the model by an order of magnitude. In this example, the model of a 5-axis milling machine was used.

To ensure that the machine can subsequently locate points according to the specifications of the NC control unit, so-called 'transformation nodes' must be generated. In the simulation, these transformation nodes serve as sensors to which the current axis values are assigned in order to be able to relocate the machine model's points. Thus, for the 5-axis milling machine illustrated in Fig. 2, five of these transformation nodes are necessary; these reflect the machines' individual axes.

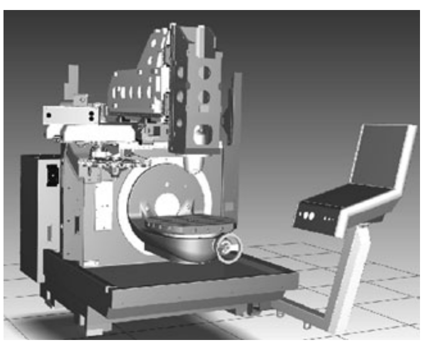

Fig. 2 Model of the 5-axis milling machine after the optimization process

3.3 Connect the CNC with the Virtual Machine Tool

If the machine is configured on the NC control unit and the NC program to be tested is likewise ready to replay on the control unit, then only the connection between the NC control unit and the virtual machine model remains to be implemented. As illustrated in Fig. 3, the current axis values for the NC control unit are assigned to the model of the 5-axis milling machine, which then moves according to the motion specifications provided by the control unit. In this manner, all collisions between machine axes can be discovered. In addition, errors can be detected which could impede the trouble-free run of the NC program on the NC control unit.

3.4 Material Removal

An exact NC program evaluation that includes the influence of the tool on the work piece is only possible if the work piece is generated quasi-virtually in the course of a simulation run. However, since VR models are usually based on the VRML data format (which describes the models based solely on their surfaces), no material removal can be realized. To solve this problem, a method was developed which provides the ability to load work pieces as blanks into the VR environment, then to process them virtually through the HiL coupling described above.

The unprocessed work pieces can be directly loaded as CAD models, processed, and then exported again. In this way, the processed model of the work piece can be reloaded to a standard CAD program to be examined for errors.

The VR software that re-processes the data for the VR scene has been split into two parts. The first part encompasses a mathematical simulation core that enables CAD

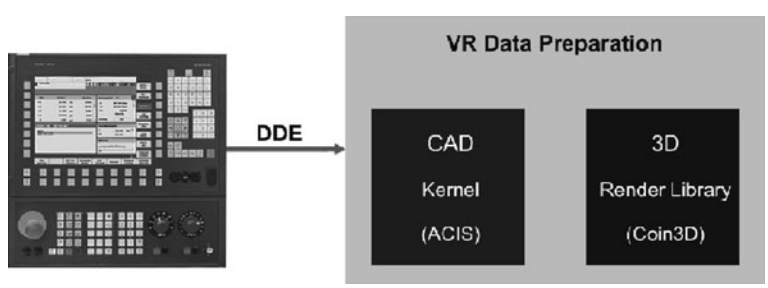

Fig. 3 VR data preparation for the realization of the material removal

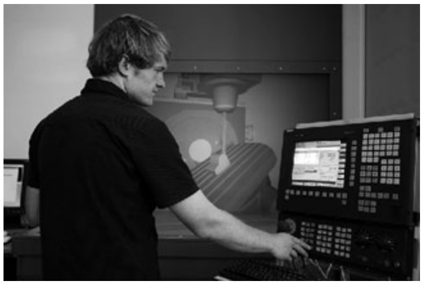

Fig. 4 HiL coupling between Siemens SINUMERIK 840Di and a virtual machine model

functionalities and Boolean operations[3] on the work piece. The second part serves to facilitate the visualization process. The ACIS CAD core from the Spatial Corporation was integrated into the mathematical simulation core. The use of a CAD core is necessary, since CAD cores describe their models as volume-based bodies. In this way, the exact calculation of the processing (material removal) is guaranteed. To visualize the scene, the OpenGL-based Coin3D rendering library was used. The final VR-based Hardware in the Loop coupling is illustrated in Fig. 4.

4 Conclusions and Outlook

In production engineering, particularly for the work processes performed by machine tools, NC programs have become the established standard description language. In simple and clearly-structured NC programs, a test for errors and collisions could still be performed manually by the machine operator. However, with ever more complicated work piece geometries (especially for free-form surfaces), this was no longer possible without a great deal of effort, since most NC programs are automatically generated and contain several hundred thousand lines of NC code.

Hardware in the Loop coupling between a real NC control unit and a virtual machine model, as presented here, enables early testing of the generated NC program. Since it is directly run on the same NC control unit on which it will subsequently also process data, additional possible sources of error are minimized. This is an enormous advantage in comparison to standard desktop-based simulation programs. The immersive VR visualization of the machine tool further simplifies the recognition of possible course errors. Then, the removal simulation culminates in the CAD export of the virtually produced work piece, along the chain, CAD→VR→CAD. This tool permits testing of the resultant geometry, even prior to the production of the actual work piece. Further potential errors which can be detected early and remedied using this simulation include: problems resulting from the post-processor, collisions between machine axes, and erroneous coordinates, such as destination points which the machine cannot reach due to its construction. In addition, temporal optimization of the NC program is possible.

There is a need for research regarding the integration of multi-body systems into the simulation, including the calculation of movable masses on the machine as well as their static, dynamic stiffness and the return of the results to the NC control unit as current actual values.

The continuing evolution of computing technology with ever-higher performance levels will enable the inclusion of the machine's process parameters in the simulation. This expansion could encompass the inclusion of repulsion forces and possible tool wear, and the prediction of tool breakage. In addition, the elastic re-shaping of the work piece (as well as the tool), dependent on relevant material parameters, could be simulated in real time. However, the risk remains that with the inclusion of all the process parameters described, useful data handling would no longer be possible. Therefore, the primary factors that are significant in the production process must be ascertained, in order to include only these in the initial simulation.

The Hardware in the Loop coupling of a real NC control unit with a virtual machine model, as described in this paper, forms a suitable basis for the integration of additional functionalities in order to make a more realistic VR-based simulation possible.

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[3] Boolean operations represent a standard process for the generation of free-form surfaces – cf. e.g., [11].

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Virtual Reality in Planning of Non-destructive Testing Solutions

N. Avgoustinov, C. Boller, G. Dobmann, and B. Wolter

Abstract Most Non-Destructive Tests (NDT) rely on effects, which are invisible without special equipment – e.g. ultrasound, X-rays, electromagnetic fields. This fact complicates the understanding of the individual inspection techniques and their handling – e.g. during calibration, optimising and documenting of tests. Therefore, suitable methods and tools have to be developed in order to improve the understanding of NDT effects – e.g., by means of modelling of the processes with consequent simulation and visualisation of the results or the process model in virtual reality (VR). Uncomplicated accessibility and usability in both technical and economical sense are key aspects for these methods and tools in order to become generally accepted and well-established.

Keywords Virtual reality · Non-destructive testing · Production planning

1 State of the Art

1.1 Non-destructive Testing

The Non-Destructive Testing (NDT, cf. e.g. [1, 2]) uses methods that are known since hundreds of years, as well as relatively new methods. Nevertheless, it is a well developed, successful and already established engineering area. Despite its successful applications, its potential is still not exhausted and an improvement of the understanding of NDT could lead to improved application methods, to better results or even to the discovery of new physical effects or methods, which could be used in NDT.

1.2 Modelling, Visualisation and Virtual Reality

The three dimensional modelling (3D-modelling) and the visualisation of 3D-models are already well established and employed in many scientific areas (product design, production planning and control, process analysis and optimisation, etc.) and recreational areas (games, cinema, etc.). On the other hand, there are still many different techniques (for modelling of the data to be visualised) in use and none of them is an optimal solution for all application areas. A short comparison is given in Table 1.

The virtual reality (VR) is nowadays usually understood as a (computer supported) technology, allowing to present not really existing[1] objects/worlds in such a manner that they could be perceived as real. Numerous definitions are available in the literature – e.g., in [3–5]. VR, augmented reality (AR, complementing real world with virtual elements) and mixed reality (MR, intermixing of real and virtual worlds) together are referred to as VR-technologies or VRT in the paper. A good overview of the VRT as well as their history are presented in [5].

In this paper we shall understand under VRT a realistic visualisation of 3D models and their behaviour, allowing on the one hand interactions with the users, and on the other hand – interactions among the models themselves. For even better results the so-called immersive VR can be used, where additional technical means are involved for achieving even better realism of the perception – stereo vision, stereo or quadraphonic sound, tracking of the user's position and orientation for achieving dynamical adjustment of the virtual world, etc.

The VRT are even newer than NDT, but enjoys a rapid development and quick popularity growth. The idea to harness VRT for developing, supporting and improving NDT

[1] They must exist at either as computer models or as some kind of perceivable representations (pictures, photographs, etc.), though!

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Table 1 Modelling techniques for 3D visualisation: traits

Method\Trait	Boundary[a] represent	Volume rendering	Ray tracing
HW-required	Normal	Mid-range	High-end
Standardisation of the data representation	Wide selection, established	Limited selection	None
Popularity	Great	Low	Low
Spreading in internet	Wide	Narrow	No
Rendering of changes in real-time	Yes; state of the art	Possible, but exceptional	Impossible on a single desktop PC[b]
Reality of static visualisation	Normal	High	Extremely high
Object size to model size ratio	>>1	Accuracy-depending	Proportional to scene's entropy
Material structure rendering	No	Yes	Yes[c]

[a]Although many CAD-systems and other modelling software use constructive solid geometry (CSG), from the rendering viewpoint it is almost equivalent to the boundary representation (B-rep).
[b]Current trend is the so-called "Real Time Ray-Tracing" – special algorithms *and* hardware for achieving ray tracing in real time (cf., [6]).
[c]Transparent materials only!

is innovative and – according to the state of the Authors' knowledge – so far not found in the technical literature. In this paper we introduce and explain the idea and our vision for its development.

1.3 Need for Visualisation and VRT in NDT

> If I can't picture it I can't understand it!
> Albert Einstein

Most methods for non-destructive testing are based on effects that are neither visible for a naked eye nor perceptible to the other human senses – e.g., ultrasound, X-rays, electromagnetic fields, etc. This impedes the understanding of the methods and their proper application. For this reason it is necessary to search for technical means that can illustrate the processes and support their understanding – for instance through creation of suitable models of the testing processes, followed by simulation and visualization – preferably by highly expressive means like VRT. The VRT, especially combined with multimedia and possibilities of interaction between the user and the models, on the one hand, and among the models or their parts, on the other hand, seems to be the most reasonable possibility for illustrating and investigating all abovementioned invisible effects and processes for the purpose of better understanding. The employment of immersive VRT can improve the comprehension and the quality of experimentation even more.

The Fraunhofer Institute for NDT (IZFP) recognized the potential of the VRT and has started to use it for optimization of its NDT-tests. Meanwhile two systems for immersive VRT are available – a table system for development activities and a larger rear projection system (power wall) for presentations, demonstrations and co-operation in larger teams. A new working group was created in order to develop dedicated application software for the VR-facilities, as well as product and process models. The models are used for simulation and visualization of different NDT applications. The VRT systems are used for illustration of NDT processes (process modelling, simulation and 3D-visualisation of all objects and their interaction), for planning of new NDT solutions, for documentation, for training and examination of NDT technical personnel, as well as for consultations concerning non-destructive test applications. Even if VRT has already found its way into industry, it is obvious, that the introduction of VRT into small and medium enterprises (SMEs) might be problematic.

1.4 VRT in Small and Medium Enterprises

Despite their advantages, the VRT-facilities are still not well suited for use in SMEs due to the following reasons:

1. Efficient VR-facilities are large and expensive;
2. Application of VR requires extended staff training and if it is used only occasionally, this training might be worthless;
3. Conventional VR-facilities are immobile and reduce the flexibility of the SME;
4. Institutions, providing VR-facilities as a service are busy to work for larger and well-paying enterprises.
5. VRT-"provider" (until now mostly research institutions) have limited resources and cannot serve all potential (SME-) clients.

A possibility to improve the situation (primarily) of SMEs could be the introduction of an innovative, Web-ready, VRT- and component-based virtual laboratory for non-destructive examinations, which could support the planning and commissioning of NDT applications, as well as allow for low-cost and efficient remote consulting and support. Similar approach was already successfully used, e.g. in [7, 8].

2 NDT-Solution: From an Idea to the Solution

Let us define the term *NDT solution* as a concept for application of NDT, together with all equipment needed and with all actions, which are necessary to implement it in the manufacturing of a given product. This implementation can be very different for already established and for newly planned manufacturing lines. In the simplest case a sensor and a measurement device are sufficient (cf. Fig. 1). Even in this extremely simple case additional auxiliary equipment like table, and electricity supply are needed, and can require either changes in the existing facilities or transport to a newly established measurement station (and possibly back).

In more complicated cases it could be necessary to embed a new measurement facility – e.g., a micro computer tomography (micro CT) machine – into an existing production line. In such cases an intensive and possibly computer aided planning is necessary, and the use of immersive VRT can be very helpful. Even more useful is the ability to simulate and visualise the behaviour of different products, devices and even whole production lines by means of VRT. It allows to eliminate concept or structure failures yet before they appear as material/real products, and allows to optimize the processes and the required NDT solution.

In general, the introduction of a new NDT-solution goes through the following steps:

1. Determining the need for an NDT-solution;
2. Problem and solution modelling;
3. Simulation and visualisation of various scenarios for ND-testing;
4. Identifying the best solution;
5. Planning, simulation and visualisation of the NDT-solution's placement and integration into the manufacturing line;
6. Training and certifying the personnel to operate the NDT equipment;
7. Provision of NDT equipment required and auxiliary equipment;
8. (Physical) Incorporation into the manufacturing line;
9. Commissioning;
10. In-use monitoring and control.

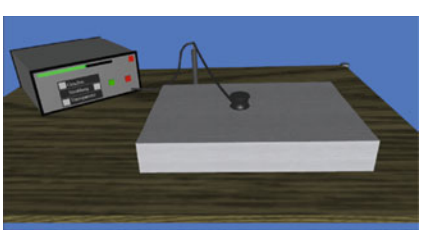

Fig. 1 Example of an arrangement for NDT. The *indicator-bar* indicates the presence of material defects

Most of these steps could benefit from computer aided support.

3 VRT-Aided NDT

Software tools for the general (i.e. non-NDT-specific) computer aided support – like in step 5 and partially in steps 2 and 10 – are well-established. However, there are no specialised software tools for supporting the NDT-specific steps 1, 2, 3 and 4, and for 6 and 10 only partial solutions exist. Unfortunately, no software product is available so far that supports all of the steps described above. The complexity of this task, though, needs a systematic approach for finding an adequate solution. Some specific details are described in the following:

3.1 Visualising the Invisible

This main problem of this task is that – despite its indispensability – it is under-defined. For instance, how should be visualised ultrasound in an intuitive and unmistakable way? How should it be distinguished from the visualisation of X-rays? How should different material defects and materials be visualised? An example-visualisation of a virtual "examination waves" and a very simplified material defect is given in Fig. 2.

Nevertheless, it is obvious that the use of 2D pictures is very inefficient and thus insufficient for the process' illustration and explanation.

In general, the measurement data contain noises and information not only about the defects but also about the material structure. The amounts of data, delivered by measurements of homogeneous materials are tiny, by measurements of composite or porous materials, respectively – huge! In both cases appropriate filtering and pre-processing is needed before the visualisation of the data can be used for analysis and

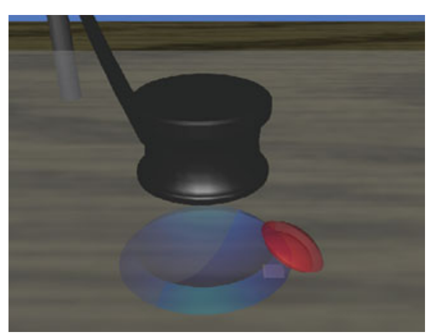

Fig. 2 Model of the propagation of examination waves (*blue*, bigger on this snapshot) and their reflection from material defects (*red*, smaller)

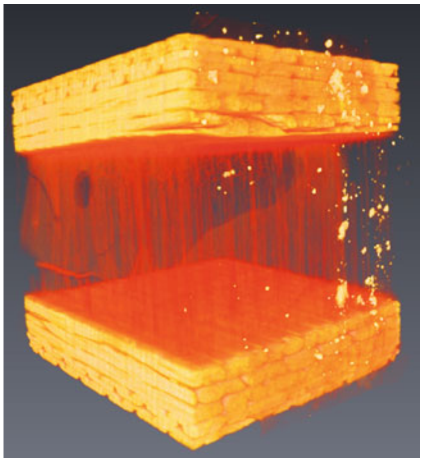

Fig. 3 CT of a composite material: both its structure and some material defects (tears) can be observed

evaluation – cf. Fig. 3, where measurement data from a computer tomography (CT) is visualised.

The analysis and the evaluation of the measurement data is another problem, requiring computer support. Depending on material, defect types, NDT method and other parameters the evaluation time could be orders of magnitude longer than the measurement time and could become days in complicated cases.

3.2 Data Fusion

Another important task is to visualise simultaneously and in the proper geometrical space on the one hand, the data from different types of NDT measurements – e.g. ultrasound and eddy current measurements, and on the other hand – also the CAD-model or photographs of the part tested (cf. Fig. 4 below). This is not a trivial task, because usually the measurement data are volumetric, and in most cases the CAD-models either come as a boundary-representation or lead to equivalent rendering. Just a few software products, that are able to mix volume rendering and b-rep rendering without a dedicated extension are available on the market, and have their price.

One of the tasks of the data fusion is to visualise the data from the different measurements and the model of the measured part on their correct poses (i.e., position and orientation) in the virtual space. This could be a problem, because often the different data sets and the part model do not contain common reference points.

3.3 The Data Flow (Data Processing Flow)

Some NDT inspections are performed with the aim to give a yes/no answer to the question "should the part tested be rejected as defective" or not, some have to give a quantitative answer to "how good/bad is the part tested". In both cases, though, the processing of the measurement data goes through several steps, forming the so-called data processing flow (DPF).

Most steps are necessary by all NDT methods, some are optional for some of the methods, and few steps are either not needed or impossible for some of the methods. All possible steps can be grouped in the following six phases (cf. Fig. 5 where phases 2 and 3, as well as phases 5 and 6 are grouped together for simplicity):

1. measurement (data acquisition)
2. data/model reconstruction
3. data fusion
4. visualisation
5. interpretation of the results
6. evaluation (or taking a decision about rejecting).

Phases 2 and 3 are sometimes called pre-processing because they take place before visualisation; for similar reasons phases 5 and 6 are sometimes called post-processing. It is obvious, that all NDT methods need (user-friendly) visualisation of the data they have gathered. In this case the term "visualisation" is used in a wider sense and includes the results of all types of testing methods – such that deliver images, such that deliver 3D-models and even methods, delivering only a single signal. The last case is not of special

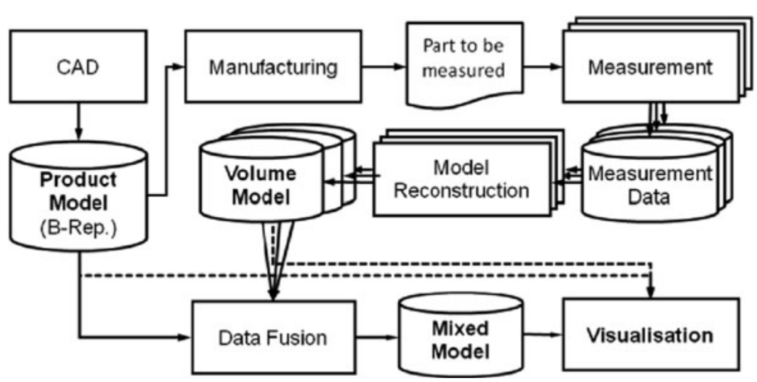

Fig. 4 Simplified scheme of the sources and types of the data to be visualised

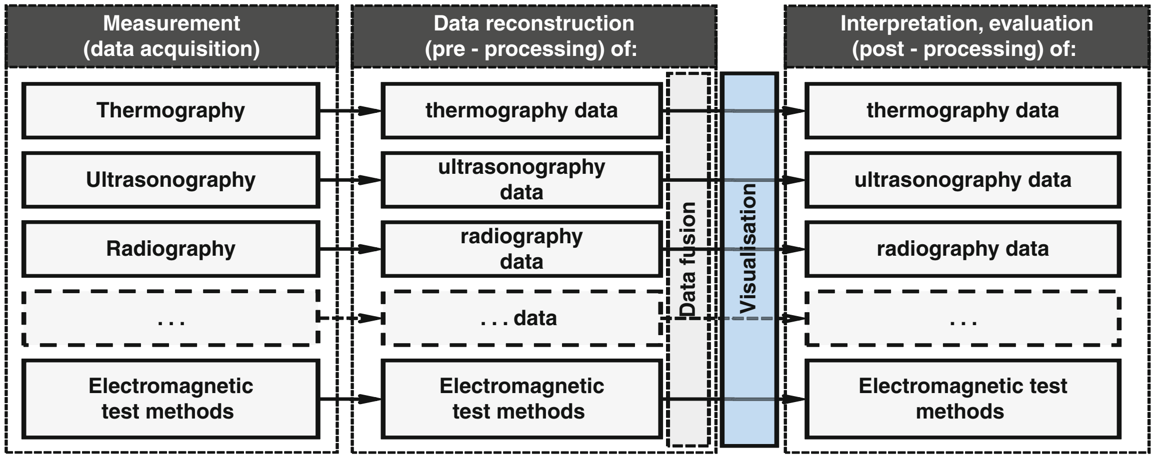

Fig. 5 Data flow and data processing when multiple NDT methods have to be used

interest for us, because it is the simplest case and visualisation could be a red or green light on the measuring device. But the more voluminous the data to be visualised is, the more complicated its processing becomes and the greater potential for optimisation exists. For instance, although in the practice each team or expert usually specialises in the development (respectively in the use) of either one NDT method or a group of related NDT methods, the processing of the delivered measurement data undergoes many similar steps. Factoring out such processing (cf. Fig. 6 below) would allow better distribution of the work among experts on different processing, as well as better specialisation of those experts.

Visualisation is the area that could benefit most from such reorganisation of the DPF, because it becomes a place of technology transfer, where each improvement, developed due to a requested from a specific NDT method could be immediately applied to every other NDT method that could also benefit from that improvement. Therefore, such optimisation of the DPF can be quite efficient.

4 Our Vision

Stereoscopic visualisation is becoming well-established within many scientific areas and is considered to be the most adequate representation for complex products and processes. The display and input devices still being expensive turn out to be a financial barrier for many potential users – however with prices dropping rapidly. Today, 3D-visualization has started to develop to an affordable end-user product (see 3D-TVs, monitors and displays in actual notebooks) that eases the way to stereo-visualisation additionally. On the other hand, the internet is turning into The Medium and The Tool for everything (see YouTube 3D-movies). Moreover, since the standardisation of the second version of the Virtual Reality Modelling Language (VRML, cf. [9] numerous improved approaches for efficient representation of 3D and VR data within an internet/browsers are emerging – Web3D/ X3D (Web3D consortium), O3D

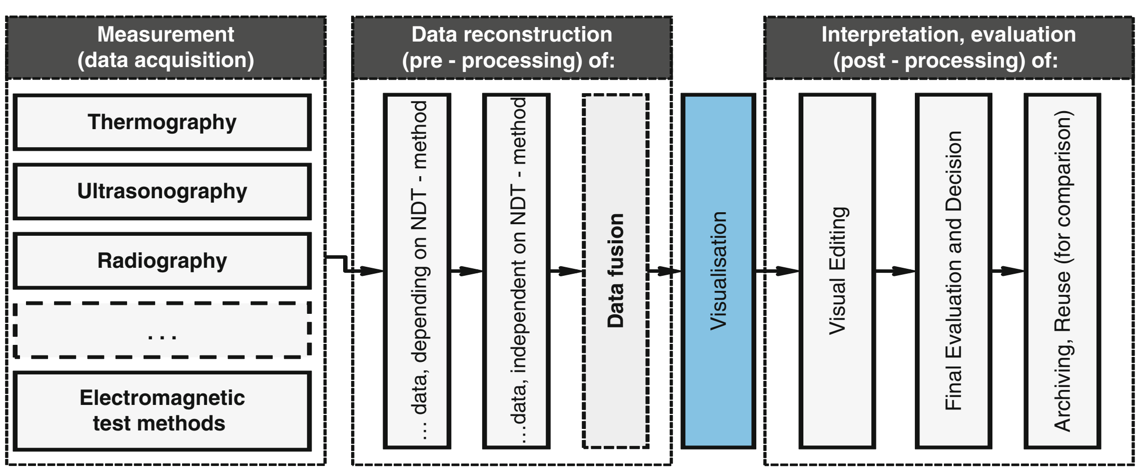

Fig. 6 Optimised data flow and data processing when multiple NDT methods have to be used

(Google), WebGL (the Khronos Group), X3DOM, XML3D (Saarland University).

We are working on an approach that would allow to flexibly join these two key technologies and make multimedia-enriched 3D models of complex processes like NDT possible experience by using either a conventional or – when desired – stereoscopic displays. One of the challenges we are facing is the choice of the appropriate format, so that the models created remain compatible and usable with models from different sources in the future, too.

Our vision is to develop a heterogeneous, expert-system-like, intelligent environment that can assist even non-experienced users during the introduction of NDT-solutions (cf. the steps, mentioned in Sect. 2) and in addition addresses/improves some NDT-specific challenges. First results are already harvested, and the prototype of our system is on the way to its implementation.

5 The Challenges

At least the following challenges exist at the moment:

1. Creating intuitively understandable (i.e., even without preliminary explanations) illustrations of all invisible effects in use;
2. Modelling and visualising all kinds of (material) defects using the same basis;
3. Efficient representation and visualisation of huge amounts of data;
4. Ability to handle/visualise B-Rep, voxel and mixed representations of 3D-data;
5. Factoring out the visualisation of different NDT-methods (cf. Fig. 6 above);
6. Data fusion and information fusion;
7. Overlay and integration of heterogeneous information;
8. Enabling the comparison of different measurements of one and the same product during its lifetime for analysing and documenting the history of the material degradation.
9. (Automated) Recognition of features in the measurement data (data mining);
10. Automating the data interpretation and evaluation;
11. Multi-scale simulation of the NDT-processes;
12. Introduction of standards for representation of measurement data (where sensible/applicable);
13. Introducing methods for interpretation and evaluation that reduce the subjective factor.[2]
14. Making the solutions for all challenges enough efficient for making most of the DPF steps possible to be performed on standard office computers as well as over internet (with server-side support when necessary).

6 Summary and Outlook

This is a work in progress and there is still much to be done. Although the vision sounds ambitious, our first experiments and prototypes (cf. [10, 11]) show that in the long run most ideas of this vision remain realistic and very promising. Some of the few remaining questions require intensive co-operative work with other partners and institutions.

Acknowledgments Many thanks to Dr. Michael Maisl for providing the CT-data, as well as for explaining what they do contain. We are also grateful to Christoph Speicher who implemented most of the process models and some of the necessary data converters.

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[2] A well known problem is that two different NDT examiners can evaluate one and the same measurement data differently. The interpretation could vary increasingly with decreasing flaw size to be assessed, which requires a probability of detection (POD) to be provided for each inspector accordingly. It is expected to get this POD enhanced through VR-NDT.

A Systems Approach to Hybrid Design: Fused Deposition Modeling and CNC Machining

V. Townsend and R.J. Urbanic

Abstract Different manufacturing processes typically do not evolve collectively; often one technology evolves to do what another cannot and reaches new depths of potential. Rather than competing in separate systems, connecting these processes as a shared system utilizes the strengths of both and creates a foundation for collaborative (hybrid) design and manufacturing. This chapter explores a methodology that harnesses knowledge of different processes (Fused Deposition Modeling and CNC machining), through the Analytic Hierarchy Process, effectively designing and manufacturing the best part. Managing complexity in modularization, this hybrid methodology is tested in application through case study (casting pattern design and manufacture).

Keywords Hybrid design and manufacturing · Additive manufacturing · Machining · Analytic Hierarchy Process (AHP)

1 Introduction

Purposeful systems (teleological) are coupled to their environment, and are guided by and oriented to the goal of the system [1]. This approach is foundational to hybrid design, where the function and inherent value of a part (or product) are not a step in, but rather in every step of, the design and manufacturing process.

Hybrid design involves process comparisons. Process comparisons typically consider processes as separate alternatives to solve one problem. However, an answer is always relative to how the problem is constructed. Herein, the problem (design and manufacturing of a part) is decomposed into modules in the design and manufacturing domains, effectively managing complexity; alternative solutions are combined and synthesized to determine the most effective solution.

Thus, while process comparisons typically answer the question 'what is best'; in contrast, this chapter strives to answer the question 'how can the processes collaborate in creative partnership' with the goal of designing and manufacturing the best part. Understanding the relationships of processes, strengths and weaknesses, is consequently foundational to hybrid design.

In this chapter, process comparisons are drawn between additive manufacturing (specifically Fused Deposition Modeling) and CNC (Computer Numerically Controlled) machining. Rapid prototyping, including Fused Deposition Modeling (FDM), is well described in [2–5]. The term 'additive manufacturing' has been deemed preferable to 'rapid prototyping' by ASTM committee F42 [6, 7]; thus the former term will be utilized in this chapter henceforth. In comparison to machining, additive manufacturing is not constrained by draft angle, internal geometries, jig and fixture designs, etc. [8]. Additive manufacturing integrates the information and material forming processes, such that non-homogeneous material properties can be created [9]. Drawbacks of additive manufacturing versus CNC machining include surface finish quality [8], part accuracy [10–14], limited materials [4], residual stress leading to deformation and the conflict between precision and forming velocity [9]. Specifically for FDM, mechanical properties (i.e. tensile strength, elastic modulus, compressive strength) depend on part orientation with respect to the substrate and the build material path [15–18]. Support material removal is also a consideration in FDM, as finishing is a post-process; conversely, in CNC machining finishing can be integrated into process planning.

Through strength and weakness comparison of additive manufacturing and CNC machining, the complementary nature of these two processes is evident. How and where these processes can work best together involves systematic decision-making, engaging knowledge in a rational manner.

To incorporate intangible and qualitative considerations, which are profuse in hybrid design, the Analytic Hierarchy

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A. Bernard (ed.), *Global Product Development*,
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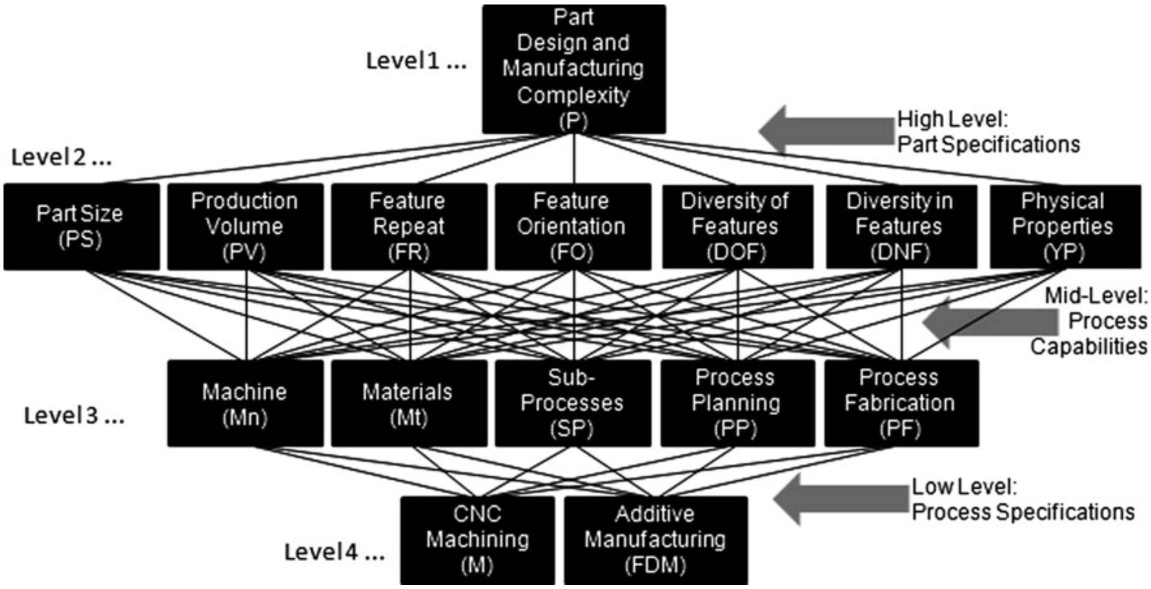

Fig. 1 Analytic hierarchy of hybrid design and manufacturing (FDM and CNC machining)

Process provides a suitable decision-making structure. In the conventional Analytic Hierarchy Process (AHP) developed by Saaty, a nine-point scale is used to rate pair-wise comparisons of hierarchy components between levels as an eigenvalue approach [19]. Of benefit to hybrid design, AHP lends itself to being adjusted according to a system (to different parts) and correspondingly to knowledge (in people, and embedded in processes) of the system.

In summary, this chapter applies the Analytic Hierarchy Process (AHP) to create a decision making methodology for hybrid design and manufacturing, for CNC machining and additive manufacturing (FDM). Modularization is explored and derived in conjunction with the decision-making model, effectively managing complexity, and creating the most effective design and manufacture of a part. General guidelines are derived from the methodology represented in Fig. 1. The methodology's effectiveness is tested in a physical application. This case study consists of the hybrid design and manufacture of a complex sand casting pattern, used to cast the part.

2 Related Work

2.1 *Decision-Making in Additive Manufacturing*

Vaidya and Kumar analyze 154 papers that apply AHP, of which 18% are manufacturing-related [20]. Li and Huang apply AHP to design in conjunction with TRIZ (Russian Theory of Inventive Problem Solving) [21]. In Li and Huang's work, a manufacturing system is proposed based on a pre-determined part design, whereas this chapter focuses on developing part design and manufacturing relative to a manufacturing system.

Kengpol and O'Brien apply AHP to additive manufacturing (as a Time Compression Technology, TCT); the focus is evaluating the investment in TCT as a strategic decision based on new product success [22]. CNC machining is not compared. Armillotta discusses a decision model for fifteen different layered manufacturing techniques, including FDM, and a sixteenth alternative of CNC machining of aluminium [23]. Also included is the model's application to casting pattern design (although CNC machining is not compared for this application). The focus is selecting between different additive manufacturing processes; thus, criteria used in the AHP do not fully explore differences between additive manufacturing and CNC machining (i.e. process planning is not mentioned). These differences are explored more fully in this chapter along with considering the part's geometric complexity. Lastly, Armillotta considers the part's (or product's) application as a level in the hierarchy; conversely, the model developed in this chapter is teleologically based. Modularization in hybrid design is also not discussed by Armillotta.

Other decision-making techniques have been utilized to select one additive manufacturing process over another. Rao and Padmanabhan utilize a graph theory and matrix approach for rapid prototyping process selection [24]. Fuzzy decision making is applied by Mahesh et al. [25]. Masood and Soo compare additive manufacturing systems for purchase [26]. Decision support to select FDM variables is developed by Ziemian and Crawn [27]. AHP has been used in multiple manufacturing related applications; in addition, it is applied in this hybrid design and manufacturing research.

2.2 *Additive Manufacturing and Tooling*

A comprehensive overview of additive manufacturing and tooling is given by Levy et al. [28]. Mueller and Kochan utilize additive manufacturing specifically with patternmaking [29]; this is also described by Rosochowski and Matuszak [30].

2.3 *Additive Manufacturing and CNC Machining*

Additive manufacturing and machining processes are typically combined to utilize additive manufacturing and then machine the same part (i.e. for better part accuracy) [8, 31–33]. Concepts are sometimes borrowed from one process to improve another; Frank et al. describe new techniques for CNC machining based on rapid prototyping concepts [34].

Table 1 Design structure matrix for FDM additive manufacturing process variables

	Mn	Mt		SP		PP				PF	
						PP-FT	PP-FP				
	Build envelope size	Build material	Support material	Finishing Operations	Support material path type	Nozzle	Part orientation	Layer thickness	Build material path type	Fabrication Time	Process Accuracy
	U	V	W	X	Y	Z	AA	BB	CC	S	T
U	1						1				
V		1	1	1	1		1	1	1		
W		1	1	1	1				1		
X		1	1	1	1						
Y		1	1	1	1						
Z		1	1			1					
AA		1	1	1	1		1		1		
BB		1		1				1	1		
CC		1	1	1	1		1	1	1		
Sum	1		15		13				13		

3 Hybrid Design and Manufacturing Methodology

The AHP hybrid design and manufacturing model is illustrated in Fig. 1. It is designed to be flexible, adjustable, and provide a comprehensive process comparison for hybrid design. The process comparison of focus for Fig. 1 is the Fused Deposition Modeling (FDM) additive manufacturing process and CNC machining.

Saaty showed that AHP levels can be organized in many ways. In Fig. 1, the AHP model is structured to transfer relationships from part specifications, through process capability, into process specifications (and vice versa). Variables in each level are described in detail in the forthcoming sections (Sects. 3.1, 3.2, and 3.3).

3.1 *Low Level Hierarchy Pairwise Comparison*

AHP pairwise comparisons are performed from the bottom of the hierarchy to the top, and are described as such herein, beginning with Levels 3 and 4. Level 3 contains process inputs: Machine (Mn), Materials (Mt), Sub-Processes (SP), and Process-Planning (PP). Level 3 also contains Process Fabrication (PF), which is a process output. Level 3 variables are described with sub-parameters in Tables 1 and 2 for additive manufacturing (FDM) and CNC machining respectively.

Tables 1 and 2 are design structure matrices and are read in the y direction as 'y affects x' and in the x directions as 'x is affected by y'. The number '1' represents a decision and relationship. The number '1' highlighted in grey indicates a highly coupled relationship.

Process Planning (PP) includes PP-FT (Fabrication Tools), PP-FP (Fabrication Process) and PP-F (Finishing Process) – the latter for machining only, as finishing is included as a Sub-Process (SP) for FDM. The Sub-Process (SP) for CNC focuses on fixturing.

Process Fabrication (PF) values are not included in Table 1 nor Table 2 (not to be confused with PP-FP), because it is an output of the decision process rather than an input. Process Fabrication is compared from FDM build time and machining time, in addition to process accuracy (which includes surface finish and other geometric dimensioning and tolerancing).

For the low-level hierarchy pairwise comparison (level 4 to level 3), the sums found in Tables 1 and 2 are compared (FDM vs. CNC machining). These ratios are translated into values in the AHP pairwise comparison utilizing values found in Table 3. Table 3 illustrates that as the ratio increases the level of complexity (decision making and knowledge required) in the process increases.

Table 2 Design structure matrix for CNC machining process variables

	Mn		Mt		SP			PP										PF	
								PP-FT			PP-FP						PP-F		
	Axis	Table dimensions	Metalworking fluid	Material Type	Locating surfaces	Clamping / supporting surfaces	Accessibility	Cutting Tool type	Cutting Tool Dimension	Cutting Tool Material	Lead in, Lead out	Single or Multiple passes	Feeds	Speeds	Path optimization	Order of operations	Obstacle interference and avoidance	Finishing Operations	Fabrication Time	Process Accuracy
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
A	1														1	1	1			
B		1													1		1			
C			1	1				1		1			1	1	1					
D			1	1				1	1	1		1	1	1				1		
E					1	1	1				1				1	1	1			
F					1	1	1				1				1	1	1			
G					1	1	1	1	1		1				1	1	1			
H			1	1				1	1	1	1	1	1	1	1	1	1	1		
I				1			1	1	1	1	1	1	1	1	1	1	1	1		
J								1	1	1		1	1	1				1		
K						1					1		1	1	1	1	1			
L												1						1		
M								1	1	1	1	1	1	1	1			1		
N								1	1	1	1	1	1	1	1			1		
O					1			1	1	1	1	1	1	1	1	1	1	1		
P					1	1		1	1	1	1	1			1	1	1	1		
Q					1	1	1				1	1			1	1	1			
R												1	1	1	1	1		1		
Sum		2		7			17											117		

Table 3 Hierarchy pairwise comparison values

Value in AHP	Ratio	Complexity of One Process vs. Other
1	1.0 – 1.4	Equal
2	1.5 – 2.4	↓
3	2.5 – 3.4	
4	3.5 – 4.4	
5	4.5 – 5.9	
6	6.0 - 7.9	
7	8.0 - 9.9	
8	10 - 11.9	
9	12.0 +	Highly differs

From the Level 3 and 4 pairwise comparison, the matrix of vector priorities – Level 4 (M, FDM) × Level 3 (Mn, Mt, SP, PP, PF) is:

$$\begin{bmatrix} 0.67 & 0.33 & 0.50 & 0.88 & 0.10 \\ 0.33 & 0.67 & 0.50 & 0.13 & 0.90 \end{bmatrix} \quad (1)$$

The consistency index (CI) is a measure of deviation from consistency, where λ_{max} is the maximum or principal eigenvalue and n is the number of activities in the matrix.

$$CI = (\lambda_{max} - n)/(n - 1) \quad (2)$$

The consistency ratio (CR) is a ratio of the consistency index to the average random index (RI). RI's are specified by Saaty [19]. CR values related to Eq. (1) are:

$$CR_{Mn} = CR_{Mt} = CR_{SP} = CR_{PP} = CR_{PF} = 0.000$$

$$\text{(Less than 0.10, the critical CR value).}$$

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3.2 Mid-Level Hierarchy Pairwise Comparison

Level 2 contains seven different categories of part specifications. The following four geometric-related categories are specified in more detail.

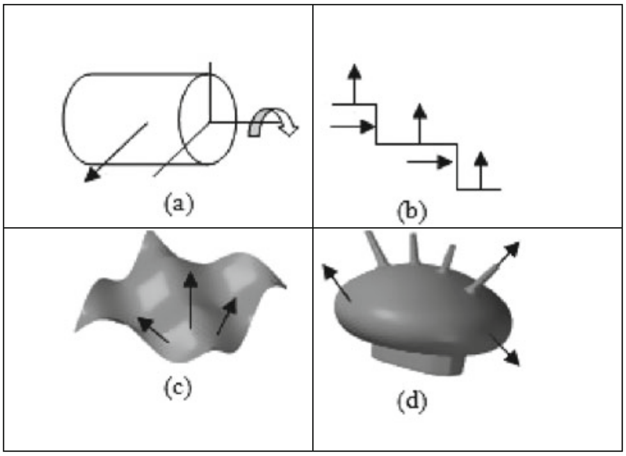

Fig. 2 Diversity in features (DNF)

- Feature Repeat (FR) – the same feature repeated with the same attributes (i.e. holes of the same size).
- Feature Orientation (FO) – the variety of feature(s)' axis alignment in x, y, and/or z-axis relative to the direction of the fabrication tool(s) (FT).
- Diversity of Features (DOF) – the number of different features (i.e. hole, chamfer, radius, etc.)
- Diversity in Features (DNF) – the movement of the surface normal over geometry, illustrated in Fig. 2. Figure 2a and b show patterning of surface normal in angularity. However, Fig. 2c and d illustrate geometry with no (or a complex) pattern of surface normal, where the normal moves along the surface rotating around multiple axes at the same time.

Relationships between Level 2 and 3 in the analytic hierarchy are summarized in Table 4 for CNC machining and for additive manufacturing (FDM). The number 1 denotes a relationship while 3 denotes a strong relationship. A ratio is calculated as Machine (Mn): Material (Mt): Sub-Process (SP): Process Planning (PP): Process Fabrication (PF) from the highest values for each variable. The ratio reflects the effort (decision-making) in Level 3 to manage complexity in Level 2. The highest values for each variable are highlighted in grey.

For the mid-level hierarchy AHP pairwise comparison, the ratios (CNC machining vs. FDM) found in Table 4 are translated into values in the AHP pairwise comparison utilizing values found in Table 3.

From the Level 2 and 3 pairwise comparison, the matrix of vector priorities – Level 3 (Mn, Mt, SP, PP, PF) × Level 2 (PS, PV, FR, FO, DOF, DNF, YP) is:

$$\begin{bmatrix} 0.14 & 0.05 & 0.08 & 0.16 & 0.05 & 0.10 & 0.06 \\ 0.29 & 0.33 & 0.08 & 0.05 & 0.05 & 0.04 & 0.36 \\ 0.14 & 0.19 & 0.25 & 0.31 & 0.13 & 0.20 & 0.12 \\ 0.14 & 0.10 & 0.50 & 0.34 & 0.63 & 0.55 & 0.34 \\ 0.29 & 0.33 & 0.08 & 0.14 & 0.13 & 0.11 & 0.12 \end{bmatrix} \tag{3}$$

CR values related to Eq. (3) are: $CR_{PS} = 0.000$, $CR_{PV} = 0.003$, $CR_{FR} = 0.000$, $CR_{FO} = 0.005$, $CR_{DOF} = 0.026$, $CR_{DNF} = 0.019$, and$CR_{YP} = 0.001$. All CR values are less than 0.10, the critical CR value.

3.3 High-Level Hierarchy Pairwise Comparison

The relationships between Level 1 and 2 relate the part to be designed and manufactured to part specifications. Used to generate general rules, the Level 1 and 2 pairwise matrix of vector priorities, focused on part size (PS) is shown as Level 1 (P) × Level 2 (PS, PV, FR, FO, DOF, DNF, YP):

$$\begin{bmatrix} 0.60 & 0.07 & 0.07 & 0.07 & 0.07 & 0.07 & 0.07 \end{bmatrix} \tag{4}$$

The CR value is $CR_P = 0.000$

Table 4 Analytic hierarchy Level 2 and Level 3 relationships for CNC machining and FDM

	CNC Machining																				Additive Manufacturing (FDM)											Highest Values				
	Mn		Mt		SP			PP											PF		Mn	Mt		SP		PP				PF		Mn	Mt	SP	PP	PF
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	S	T					
Part Size		3		3	1	1	1		1			1	1	1					1		3	3	3	1				1	1	3	3	3	6	3	4	6
Production Volume			1	3						1								1	3			3	3	3	1			1	1	3	3	0	6	4	2	6
Feature Repeat					1	1	1								3	1	1	1	1					3								0	0	3	6	1
Feature Orientation	3	1			1	1	1		1		1				3	1	1	1	3					3	3		1	1	3			4	0	6	8	3
Diversity of Features					1	1	1	3	3		1	1	3	3	3	3	3	3	3					3			1	1				0	0	3	26	3
Diversity in features	3				1	1	1	3	3	1	1	3	3	3		3		3	3	1				3	3		3	3	3			3	0	6	23	4
Physical Properties				3	1	1			1	1			1	1				1	1	1		3	3	1	1		1	1	3	1	1	0	6	2	5	2

3.4 Overview of the Hybrid Design and Manufacturing Methodology

The proposed hybrid design and manufacturing methodology takes the functional requirements of a part or product and relates them to process capabilities through the Analytic Hierarchy Process (AHP). AHP explores why and how a part (or module) can be manufactured, explored in tandem with modularization which defines what and where. Throughout the hybrid design and manufacturing methodology, represented as gears in Fig. 3, knowledge is the lubrication in the purposeful-driven teleological system.

Fig. 3 Methodology of hybrid design and manfacturing as a system

4 General Comparison Generated by the Methodology

For the following part specifications, when dominant in part design, the hybrid design and manufacturing methodology suggests preference for the outlined process (Table 5) that has the lower resultant eigenvalue (measure of less complexity):

Table 5 General guidelines for part/module specification and preferred process

Specification (in Part or Module)	Resultant Eigenvalues M (CNC)	FDM
Part Size (PS)	0.49	0.53
Part Volume (PV)	0.47	0.55
Feature Repeat (FR)	0.62	0.40
Feature Orientation (FO)	0.59	0.43
Diversity of Features (DOF)	0.64	0.38
Diversity in Features (DNF)	0.63	0.39

Thus, the following general guidelines support a starting point for module identification and quick process comparison:

- For complex geometries and high geometric diversity, additive manufacturing is best-suited
- For relatively large parts and high volume, CNC machining is typically best suited; however, large parts can be decomposed into smaller parts through modularization for further process analysis. Modules can be identified using the methodology and feature-focused general guidelines.

The value of the proposed hybrid design and manufacturing methodology is its ability to inform a solution in combinations of part specifications. This is further explored via case study.

5 Case Study of a Casting Pattern

A sand casting pattern is designed and manufactured for a high feature V8 engine section. Meeting with Nemak Canada, three areas (both cylinders and bulkhead) are considered critical for modularization, since they are areas susceptible to future design changes; these areas are later identified with modules in Fig. 4 (A, C, E) and Fig. 5 (A, C, E). The pattern design includes complex geometry, thin walls, draft on all features, and critical surface finish.

5.1 Applying the Hybrid Design and Manufacture Methodology

After collecting information from the industrial partner, Nemak Canada, the hybrid model of design and manufacture is applied in the following steps:

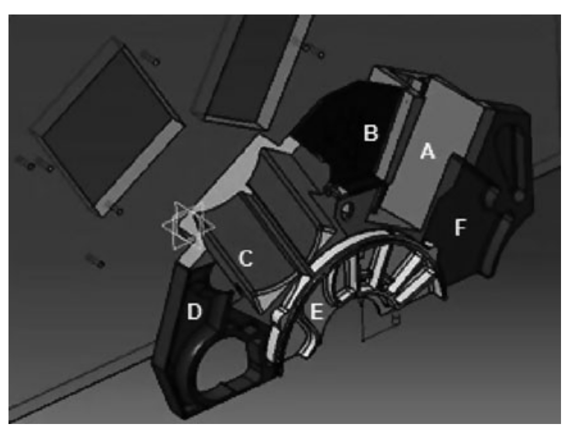

Fig. 4 Casting pattern (drag) with module identification

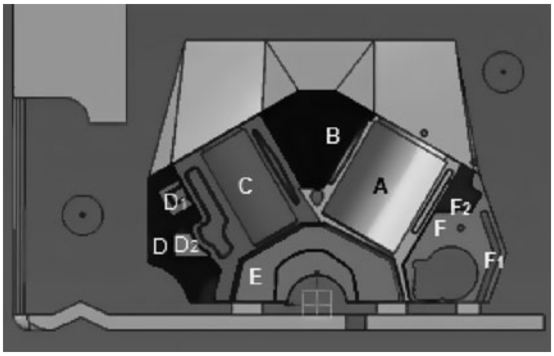

Fig. 5 Casting pattern (cope) with module identification

Table 6 Case study casting pattern modules with preferred process

Casting Pattern Drag (Figure 4)		Casting Pattern Cope (Figure 5)	
Module	Preferred Process	Module	Preferred Process
A	FDM	A	FDM
B	FDM	B	FDM
C	FDM	C	FDM
D	FDM	D	CNC
E	FDM	D1	FDM
F	FDM	D2	FDM
		E	CNC
		F	CNC
		F1	FDM
		F2	FDM

1. General guidelines from Sect. 4 are applied, in conjunction with considerations specified by the industrial partner, to identify modules. For further module clarification and identification, a critical design factor (i.e. build envelope size for the FDM process) is used in combination.
2. The AHP hybrid design and manufacturing methodology (Figs. 1 and 3) is applied to each module, lastly creating the Level 1 to 2 (high-level) pairwise comparison matrix.
3. Final eigenvalues (machining vs. FDM) resulting from the AHP are compared. The largest eigenvalue yields the most complex solution; thus, the least eigenvalue is the preferable solution.

This process is repeated for other modules and scenarios as necessary. For the casting pattern in Figs. 4 and 5, the following are considered:

- Part Volume (PV) = low (one pattern being made)
- Part Size (PS) = modules fit within build envelope
- Physical Properties (YP) = ABS (acrylonitrile butadiene styrene) plastic for additive manufacturing (FDM) is suitable. Wood is suitable for machining. The cost difference between these two materials is significant, though overall cost is not substantial because modules are relatively small and volume is low.

These specifications generally favour FDM (as suggested by the guidelines in Sect. 4). The AHP yields the preferred process results found in Table 6 with modules identified in Figs. 4 and 5.

5.2 Case Study Outcomes

The finished casting pattern modules (Figs. 6 and 7) incorporate both machining and FDM processes. Other casting pattern pieces not specified in Table 6 include: box, runner, riser, and sprue (shown in Figs. 5 and 7). These parts are machined due to simple geometry. When possible, geometric complexity is further decomposed to isolate and manage variations of complexity. An example of this is the drag pattern module B (shown in Fig. 4 as ‘B’ and in Fig. 6). For this part, a thin section with complex surface geometry is applied to a thicker machined back-plate; here complexity is further decomposed in thickness, utilizing machining for simple geometry and fused deposition modeling for more complex geometry. The casting pattern is hybrid designed and manufactured and used to cast a final part successfully (Fig. 8).

Fig. 6 Drag casting pattern FDM modules

Fig. 7 Casting pattern (drag) hybrid design and manufacture including modular assembly

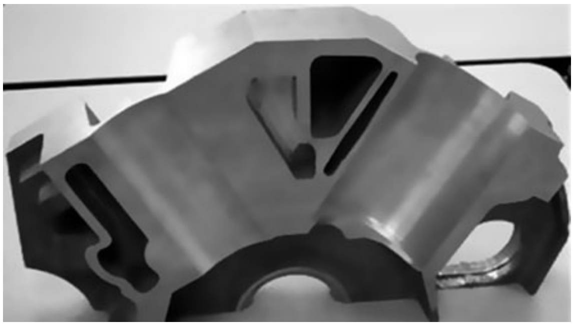

Fig. 8 Final cast part (cope side)

6 Discussion

6.1 Part Accuracy

Despite the literature on part accuracy in FDM (Sect. 1), part accuracy is somewhat unpredictable. Distortion in thick parts (modules) occurred (in the cope module B, for instance). Accuracy is improved in FDM via build orientation. Optimal build orientation minimizes support material, thereby reducing work (and the potential for error) in the finishing process. Build orientation is especially significant for critical surfaces, where in this case study and application the surface will be in contact with sand, thus affecting final mould accuracy.

6.2 Concurrent Processes

Applying the proposed hybrid design methodology engages concurrent processes for overall efficiency in the system, which can exceed the efficiency attainable through a single process optimization. Simultaneous CNC machining and FDM processes are effectively used to design and manufacture a casting pattern. Flexibility is also achieved when utilizing more than one process, by expanding the breadth of resources available.

6.3 Modularization and Assembly

Modularization is an effective way to manage complexity, by organizing complexity into a manufacturing process that manages (minimizes) it best. The hybrid design methodology studied herein effectively accomplishes this goal. One of the consequences of modularization, however, is assembly. In the case study, modules are connected with dowel pins and holes for position and then secured with screws for assembly. Holes for the dowel pins are created in the FDM

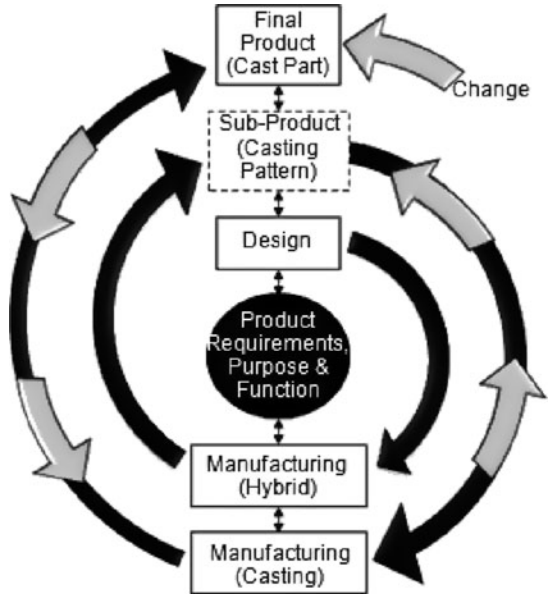

Fig. 9 Module effectiveness in change

process for relevant parts, minimizing post-manufacturing processes (i.e. machining holes for dowel pins). A machined back plate is used to connect all pieces, efficiently maximizing the accuracy attainable in the machining process; the back plate effectively serves as a datum for assembly. The machined back plate and dowel holes are visible in Fig. 4.

Modularization enables flexibility in design and manufacturing, accommodating future design changes (such as the potential areas of future modification specified by the industrial partner). In this regard, change to the overall part (the casting pattern) is minimized because change is isolated in modules. This concept is illustrated in Fig. 9. Overall, this systems approach to optimization leads to stronger design and manufacturing decisions in sustainable decision making, as opposed to solely optimizing individual parts of the system.

7 Conclusions

The proposed methodology for hybrid design and manufacture, based on AHP, supports process selection; specifically, additive manufacturing (FDM) and CNC machining are compared. The methodology adds value via the following attributes and strengths, whereby the proposed hybrid design and manufacturing methodology:

- Considers design and manufacturing in tandem
- Combines and synthesizes process alternatives (namely FDM and CNC machining) for final solution

- Accounts for modularity, managing complexity by leveraging the capabilities and advantages of comparative processes, while mitigating process weaknesses and limitations
- Is succinct and simple yet comprehensive
- Is adaptable for multiple systems by leveraging knowledge of the system relative to the methodology (as opposed to focusing on 'absolute' comparison)
- Considers function and purpose of the part being considered for hybrid design and manufacture in every step of, as opposed to a single step in, the methodology. This value contributes to the context of optimization, to the integrity of the final product, and to the system that designs and manufactures it (a teleological system).

In addition, general guidelines for identifying modules for additive manufacturing (FDM) versus CNC machining are proposed in Sect. 4.

8 Future Work

A more comprehensive time and cost study would be an improvement to the proposed methodology. Other future work could include incorporating weighting factors (fuzzy AHP) into the methodology, to emphasize critical design and process parameters.

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Design for Wire and Arc Additive Layer Manufacture

J. Mehnen, J. Ding, H. Lockett, and P. Kazanas

Abstract Additive Layer Manufacture (ALM) is a technique whereby freeform structures are produced by building up material in layers. RUAM (Ready-to-Use Additive Layer Manufacturing) is an innovative concept for building large scale metal ready-to-use parts. The design for RUAM has several process steps: the geometric design of the parts taking the complex process behaviour of the arc welding process into account; FEM to predict temperature and stress distributions to minimise part distortions; and efficient robot tool path design. This paper covers these essential design steps from a technical as well as practical point of view.

Keywords KeywordsManufacturing · Rapid product development · Design for manufacture

1 Introduction

New Additive Layer Manufacturing (ALM) technologies are currently subject of significant interest from industry. New wire and arc welding based technologies provide new routes to manufacture ready-to-use large metal parts. Producing large scale and high quality parts with very high deposition rates is the aim of the RUAM (Ready-to-Use Additive Manufacturing) machine currently being developed at Cranfield University.

Aerospace industry estimates requirements of about 20 million tonnes of billet material over the next 20 years. With machining rates of ca. 90% and ever increasing material costs especially in titanium [1], conventional manufacturing strategies need reconsideration. The RUAM concept aims at reducing production costs by providing a new, sustainable, cost and time efficient manufacturing process which utilises well established as well as advanced cutting-edge technology.

RUAM workpieces are produced by building up of material in layers (see Fig. 1). New technologies such as CMT (Cold Metal Transfer) or Interpulse Welding allow for high deposition rates being more than 10 times faster than conventional powder based technologies (Fig. 2).

In order to achieve a well integrated process that utilises the full power of the additive layer manufacture technique, each process step has to be set up and linked optimally.

Design for RUAM identifies workpiece geometries that are most suitable for the final real-world applications. For example, in aerospace new light weight stiffeners are used which need to satisfy specific mechanical constraints. ALM is an ideal way of manufacturing and testing innovative designs because ALM lowers the constraints that one typically encounters in conventional manufacturing [2–4]. The precision of the arc welding process employed in the RUAM process depends on the welding strategy. Where necessary, the rough surfaces will be ground off by the integrated RUAM machine producing high precision industrial parts. The workpieces are fully dense.

Another step in the Design for RUAM is the analysis of the temperature and stress properties of the welded

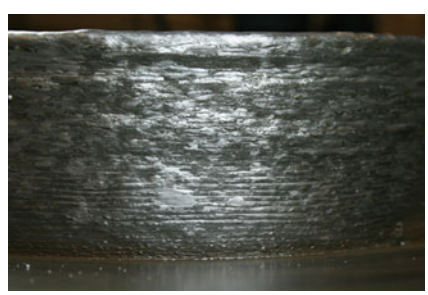

Fig. 1 Layer structure of a wire based additive layer manufacturing part

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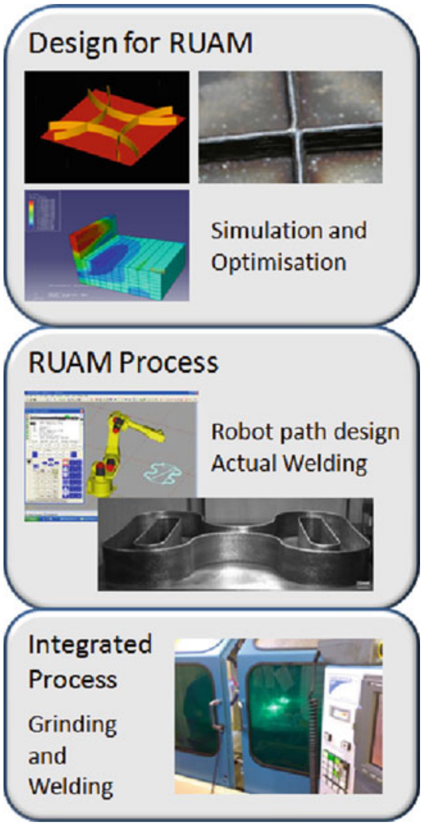

Fig. 2 RUAM process structure

workpieces. In RUAM advanced fast FEM modelling techniques are used. FEM analyses help minimising workpiece distortions by identifying the most appropriate welding tool paths.

Design for RUAM also tackles the issues of how to choose the actual welding tool paths that are technically most suitable for the arc welding process.

In the actual RUAM Process, the actual welding paths are executed by a robotic system. A robot arm guides the welding torch along a prescribed tool path. In the RUAM process, the actual robot tool paths are directly calculated from the CAD geometry. The time consuming and tedious task of teaching the robot can significantly be reduced by new RUAM tool path calculation software. Typical robot training sessions using a pendant can take hours. Now, ready-to-use tool paths are provided within a couple of minutes. The best welding parameters are applied in the actual welding process. These parameters are determined by extensive welding experiments which have been performed in steel, aluminium and titanium. These parameters determine e.g. the optimal torch travelling speed or the best wire feed speed [5].

The aim of the RUAM project is to generate large and precise metal parts rapidly using an integrated process. With RUAM up to 15 m workpieces could be manufactured by using high welding deposition rates while the precision is

Fig. 3 1000 mm × 200 mm × 4 mm RUAM titanium wall structure

provided by e.g. additional grinding steps. Precision and manufacturing time is improved by keeping the workpiece within one single machine during the whole RUAM process. The additive layer manufacturing technique has the additional advantage that, due to the sequential manufacturing technique, now sections of the workpiece can be accessed that are generally inaccessible.

The first large ALM parts have been produced successfully (Fig. 3). The travel speed was 4.5 mm/s. The time to produce this 1 m titanium part was 12.3 h. Manufacturing large components such as this wall using selective laser sintering (SLS) would be very uncommon due to the size limitations of conventional SLS machines.

Currently, the RUAM process focuses mainly on applications in aerospace industry. However, repair and cladding applications are also foci of ongoing RUAM research activities.

This paper touches on the Design for RUAM and the RUAM process itself. In particular, the design of unconventional stiffeners and their ALM manufacturing as well as FEM modelling aspects of additive layer manufacture and the automatic design of robot tool paths from CAD data will be discussed.

2 Design for RUAM

2.1 ALM Design Study

ALM has the advantage that one can manufacture parts with high levels of geometry complexity. However, also ALM has its limitations which have to be taken into account during the design for ALM. For example the achievable maximum wall thickness, material properties and some design features (e.g. maximum inclination of walls) might have an impact on the desired design.

An initial RUAM design study has investigated various designs for stiffened panes. These light weight panes can be used for aerospace applications. The ALM process allows the design of even quite unconventional structures that show a maximum buckling index. The buckling index is the buckling load per kilogram. The higher this index the better the stiffened structure. ALM parts can be designed to specific load cases and can therefore be more flexibly designed than workpieces that are fabricated e.g. from sheet metal. More recently stiffened panels have been machined from single block material. ALM provides a more sustainable solution because no material is wasted by this process.

The Design for RUAM for stiffened panels has been done first in silico. A CAD model of the stiffener was generated and FEM stress analyses performed. Five different panel designs for uni-axial loads were followed by four designs for bi-axial loads. Figure 4 shows some selected panel designs for uni-axial loads.

The results of the analyses are shown in Fig. 5. The buckling index in kN/kg has been introduced to account for the mass of a structure. A lighter structure with the same buckling load will get a higher score.

One can see that the simple unsupported plate has, of course, a very small buckling index of 3.61 and 3.71 for titanium and steel, respectively. The complex wave structure has only a slightly higher index than the plain steel plate. Thus, this design can be ruled out as a useful support solution. The corrugation design has a nearly 14 times higher buckling index than the plain plate. It is also important to notice that the corrugation is stronger in titanium than in mild steel. In our experiments this property is predominant for this type of geometry.

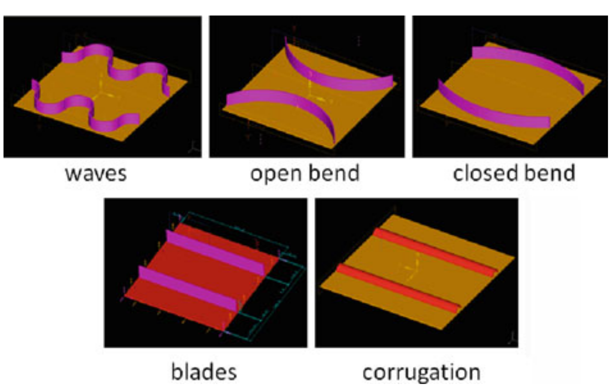

Fig. 4 Selected ALM panel designs. Uni-axial load, plate dimensions: 500 × 500 mm, stiffener height: 50 mm, materials: Ti 64, generic mild steel

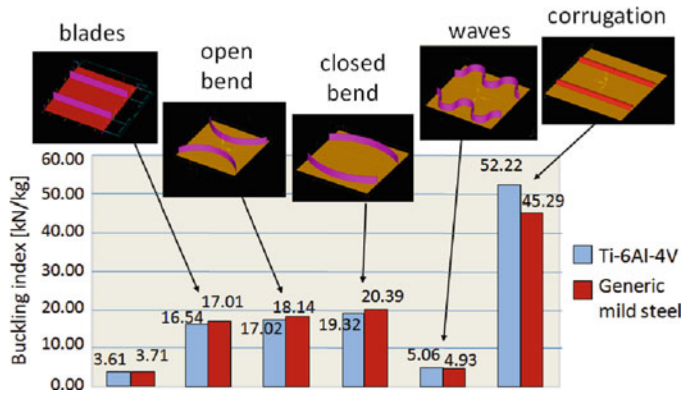

Fig. 5 Selected ALM panel designs with uni-axial load applied

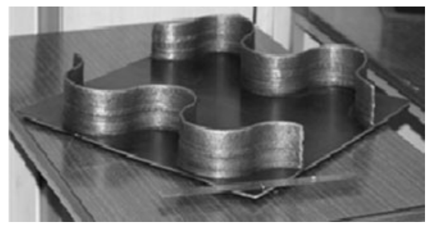

Fig. 6 Stiffened plate with wave structure using 1.0 mm wire, wire feed speed 3.3 m/min, deposition rate 1.22 kg/h, manufacturing time 2.56 h

Analysis of curvilinear stiffeners (not shown) showed some space for improvement for bi-axial loading as well. Here manufacturing cross structures becomes important.

An example of a manufactured stiffened panel produced by the RUAM process can be seen in Fig. 6.

2.2 Welding Strategies for Cross Structures in Steel

An initial investigation into the feasibility of manufacturing stiffened panel structures using wire additive layer manufacture has been performed. To date the study has focussed on the manufacture of wall crossings as shown in Fig. 7. The process utilised was the Cold Metal Transfer (CMT) which could be classified as a Gas Metal Arc Welding (GMAW) variation. The welding parameters were set to produce 4 mm wall with 0.8 mm steel wire. The torch movement is robot controlled.

The difficulties of producing wall crossing using wire based ALM are associated with the build up of peaks where the weld beads overlap at the crossing points.

A number of different build strategies have been investigated including changes to the travel speed direction and build pattern. These build strategies have a significant impact on the effective wall thickness, surface roughness and

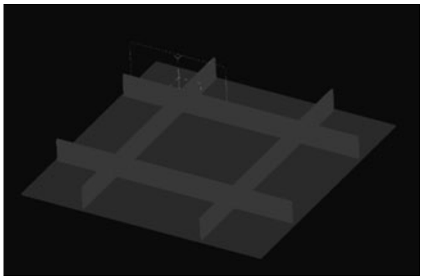

Fig. 7 Example of a stiffened panel with crossings

Fig. 8 Example of peak development

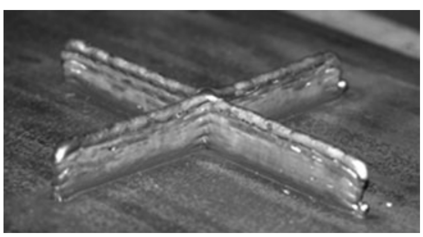

Fig. 9 Example of crossing feature manufactured using pattern of opposite angles

repeatability of the final result. The reduction or elimination of undesirable features such as stress raising sharp corners and peak development (see Fig. 8) and crossover failure in the intersection was also studied.

The experiments have demonstrated that it is possible to achieve good quality results using a pattern of opposite angles connecting at their vertices and a direct crossing pattern. The pattern of opposite angles gives the best results and produces smooth radii in the corners (see Figs. 9 and 10), but it is more complex to program. The direct crossing pattern is easier to program, but can cause sharp angles in the corners, which could act as stress raisers. Crossing features have been successfully produced with heights of up to height 100 mm and wall thicknesses of 4 mm.

Future work will concentrate on the development of build strategies for inclined walls, wall crossings with curvilinear stiffeners and wall crossings with angles other than 90°.

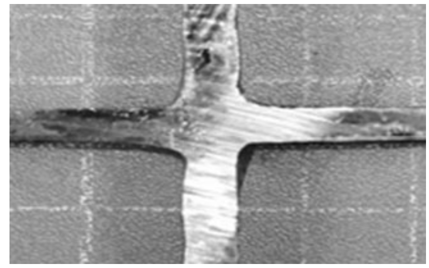

Fig. 10 Example section through crossing feature showing radii in corners

2.3 FEM Modelling of ALM Processes

The wire based welding techniques used in the RUAM project, such as GTAW and GMAW, can provide high deposition rates. However, the large heat input of these processes also brings big residual stress and distortion. These issues can badly impact the accuracy of the final shape of the parts and their mechanical properties. Therefore, it is highly important to study the thermo-mechanical behaviour of the ALM process.

FEM simulation of welding processes started from 1970s. It is widely utilised and provides accurate results for many different arc welding processes [6–8]. In contrast to these welding processes, the material in the ALM process is reheated several times. The mechanical properties cause by the reheating effect between adjacent droplets has been analysed by [9, 10].

In order to find out the optimal build patterns for building parts with minimum residual stress and distortion, studies on the thermo-mechanical performance of the ALM process has been carried out in RUAM project. The commercial FEM software ABAQUS® is employed for this task.

Three dimensional FEM models are built for the straight wall shaped ALM parts. To save computational time, only half of the parts are modelled with symmetric constrain conditions. Sequentially coupled thermo-mechanical simulation is performed in which the transient temperature distribution is applied as input for the mechanical simulation. Temperature depended material properties are used for both thermal and mechanical simulation.

The heat source is modelled using the Goldak ellipsoidal model moving along the weld bead [11]. The material adding process is modelled by activating the meshes successively with the moving heat source. The model is meshed with biased linear elements which become coarser the further they are away from the weld bead. The thermal boundary conditions include convection heat loss and radiation heat loss.

Figure 11 shows the temperature distribution of a wall with five layers. From this figure one can see that the previous

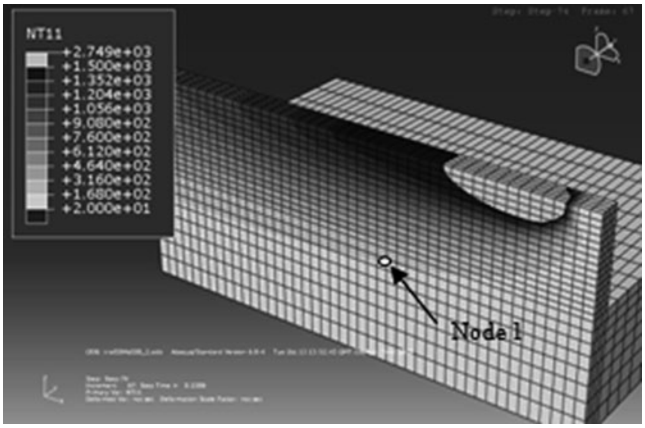

Fig. 11 Temperature simulation of the ALM process

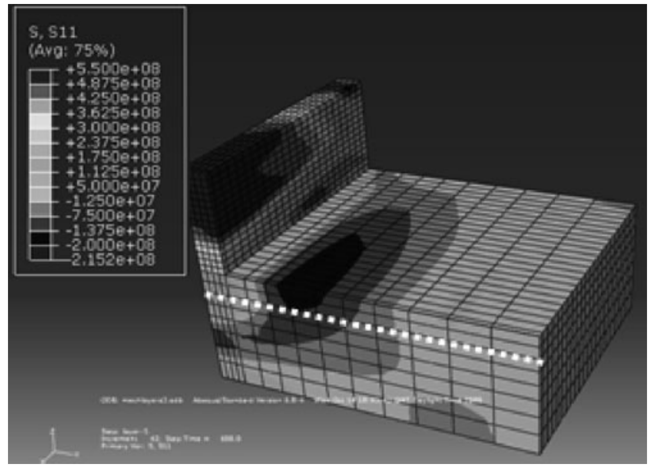

Fig. 13 Final longitudinal stress distribution. The *dotted line* indicates the points of temperature measures displayed in Fig. 14

layers are reheated when new layers are added. Figure 12 shows an example of a detailed temperature history plot of the node located on the weld central line of the middle section along the weld direction (Node 1 in Fig. 11). When the heat source passes node 1 in the first layer the material is heated up to ca. 1,800°C (max. temperature). With each further layer deposited the maximum temperature at node 1 decreases exponentially. A delay of 10 min between each pass was used to allow for the material to cool down to room temperature.

The mechanical model uses the same meshes as the thermal model but changes the element type for the stress analysis. The load imposed on the model comes from the nodal transient temperature results from the thermal simulation. Boundary constrains are added to the edge of the plate for simulating clamping conditions. Apart from using temperature dependent mechanical material properties, the plastic strain annealing phenomenon is also considered in the simulation.

The contour plot presented in Fig. 13 shows the final longitudinal stress distribution which is the main source of the distortion of the straight wall part. Notable tensile stress is located on the layered wall (ca. 550 MPa) and the compress stress is mainly distributed in the base plate near the weld bead (ca. –200 MPa).

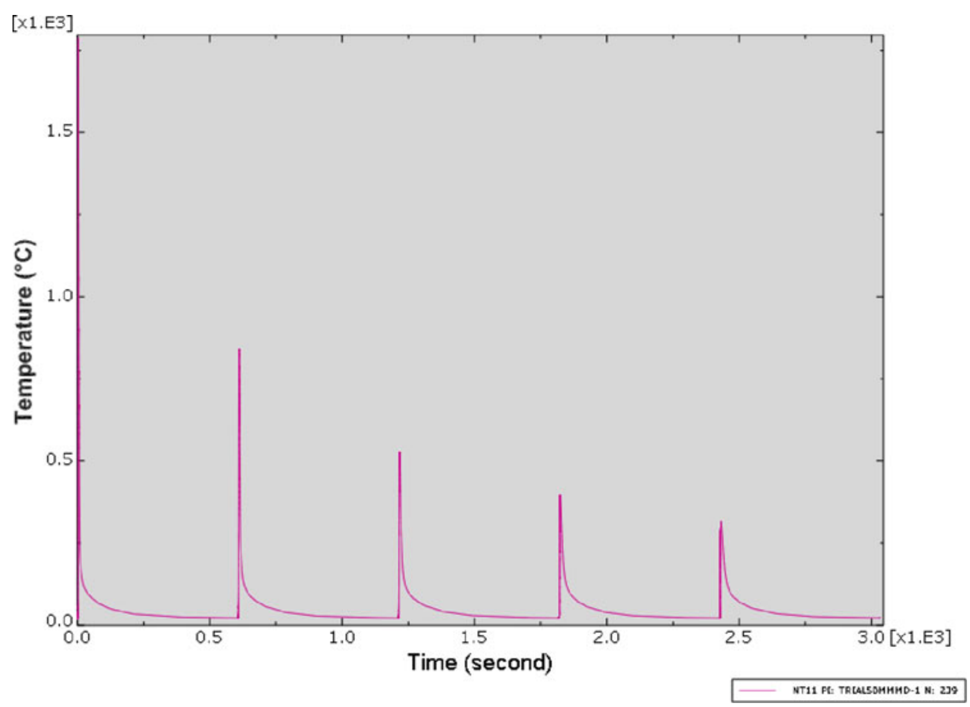

Fig. 12 An example of nodal temperature history

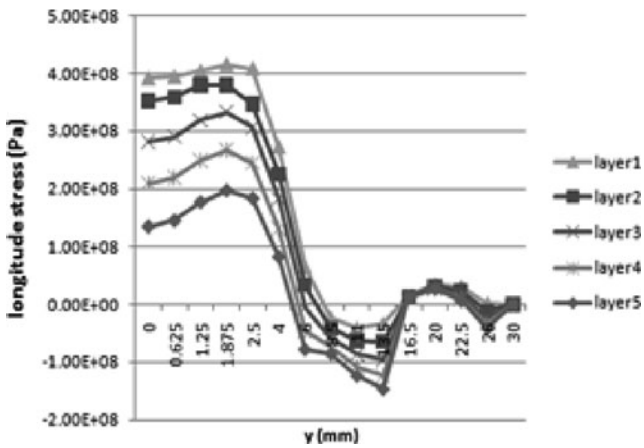

Fig. 14 Longitudinal stress plot on the symmetry plane 2 mm below the top surface of the base plate

Figure 14 shows the longitudinal stress values of points 2 mm below the top surface of the base plate and in the middle section of the part (see dotted line in Fig. 13). The different curves show the stress distribution after the deposition of each layer. From this figure one can see that the reheating effect causes a significant stress reduction whenever new layers are deposited on previous layers.

In the future the FEM model aims to reduce distortions of ALM parts by providing accurate predictions that can be used to design different welding strategies.

2.4 Robot Path Determination

In the RUAM project, a 6-axis Fanuc Robot is adopted for holding the welding torch making the ALM process very flexible. One advantage of the robot system is that it can deal with rather large parts. However, conventional robot programming with a teach pendant is generally very time-consuming especially for complex paths. Therefore, an automatic robot path generation tool is required to generate robot code directly from CAD models.

"Mirroring" milling tool paths generated from commercial CAD/CAM software or using slicing routines from Rapid Prototyping software are two ways of getting tool paths [12]. However, both these ways are not flexible because of software constrains. Therefore, researchers often develop their own tools to achieve specific part designs. Ribeiro developed a robot off-line programming system based on AutoCAD. This system can slice CAD models and generate robot programmes for ABB robots automatically [13]. Zhang developed a path planning and generation system based on the IGES format CAD models [14].

For the RUAM project, a robot path generation program RUAMROB© has been developed in Matlab 7.1. This tool contains two main modules – a slicing module and a robot program generation module. By executing these two modules automatically, the program can slice the designed ALM parts and generate the ready-to-use path code for a Fanuc robot in one go. A user-friendly interface for RUAMROB© has also been developed to simplify the setting of parameters.

The function of the slicing module generates isolines from the CAD model and produces the sequenced points on the path. The algorithm generated for this module can remove duplicate points which usually appear when CAD models with poor triangulation quality are sliced. The program also supports the user in reducing the number of output points by setting up the tolerance which is very useful for building large parts.

The robot program generation module takes these points and generates a Fanuc robot program in ASCII format. Some key parameters for the welding process can easily be set by the users, including welding process parameters such as arc on/off position, travel speed of the welding torch, waiting time between layers, building sequence for the part with several sub-parts, etc. The output robot program can be simulated and checked using the Fanuc robot off-line software ROBOGUIDE©. The software also translates the program from ASCII format into binary format that can be executed by the robot.

Figure 15 shows the general process of building an ALM part from a CAD model. The RUAMROB© program first slices the CAD model (Fig. 6a) from STL data [15] into isoline paths (Fig. 6b), and then generates the robot program which can be checked in the simulation (Fig. 6c). Figure 6d shows the manufactured ALM part using the generated robot

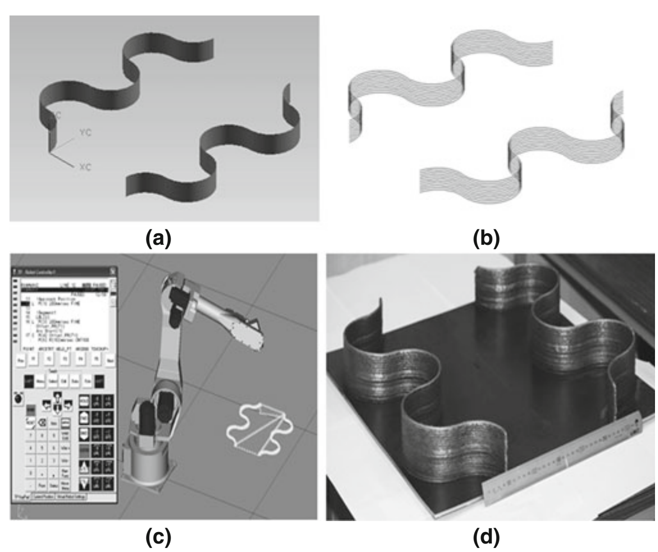

Fig. 15 Robot path generation process

program. The total time spent on the robot program generation with RUAMROB is just several minutes. Comparing to the previous experience of using a teach pedant, a huge amount of robot programming time can be saved. Moreover, it also makes building complex three dimensional ALM parts possible.

3 Summary

The RUAM process is an innovative concept that opens a vast space of options for manufacturing efficiently complex geometries. The RUAM process is especially useful e.g. in manufacturing or repairing parts for aerospace industry. Due to the high flexibility of the ALM process, these parts can be tailor made. The arc welding process provides very favourable material properties yielding ready-to-use parts.

The process chain consists of several steps that are feeding into each other. In the Design for RUAM step, new geometries are generated which have systematically been tested and optimised. This part of the RUAM project will provide a handbook for ALM incorporating design rules and features.

In order to produce high quality parts extensive experiments and simulations are needed. FEM temperature and stress analyses help understanding and improving the ALM welding process. The FEM analyses can help in minimising distortions and identifying best welding strategies. The results have been verified with examples from literature and real-world tests.

The gap from CAD design to robotic manufacture of ALM parts has been closed by an automatic path generation tool. The tool generates FANUC robot paths directly from CAD geometries. The tools paths do not integrate expert knowledge yet. Currently, directions as well as speed, etc. are decided manually following the recommendations form the design handbook, FEM analyses and welding experiments.

Future work focuses on rescaling the RUAM machine and improving the integration of each process step into one single automated smooth process. Sustainability analyses on various industry case studies are part of ongoing research.

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Characterization of Selective Laser Sintered Implant Alloys: Ti6Al4V And Co-Cr-Mo

A. Gatto, S. Bortolini, and L. Iuliano

Abstract Titanium and Cr-Co-Mo alloys are the most attractive metallic biomaterials for orthopedic and dental implants: selective laser sintering technique may use these materials but it still remains limited in terms of foreseeable performances as function of process parameters. The method essentially relies on empirical, experimental knowledge and still lacks a strong theoretical basis. This paper investigates the orientation influence on mechanical performances of Ti6Al4V grade 5 and Cr-Co-Mo specimen built by selective laser sintering. The tensile strength and the rupture surface observation allow to explain the tensile strength values obtained as a function of the fine microstructure that is confirmed by metallographic observation.

Keywords Selective laser sintering · Metallic biomaterials · Ti6Al4V · Co-Cr-Mo alloy

1 Introduction

Metallic materials are widely used for orthopedic and dental implants. Metals are more suitable for loading–bearing applications compared with ceramics or polymeric materials due to their combination of high mechanical strength and fracture toughness. Among various metallic biomaterials, titanium and Cr-Co-Mo alloys are the most attractive metallic biomaterials for orthopedic and dental implants. When metals and alloys are considered, the central aspects of biocompatibility are the corrosion resistance of materials and the influence of corrosion products on the surrounding tissue. Recently, many researchers have focused at the improvement of tribological behaviors of implant materials in order to lengthen the endoprostheses life [1–4].

Among layered manufacturing (LM) techniques, selective laser sintering (SLS) exhibits a high potential in the field of rapid manufacturing (RM), due to its capability to directly build up three-dimensional 3D metallic components [5–7].

Recent advances in metallic SLS have improved the technology although it still remains limited in terms of material versatility and foreseeable performances as function of process parameters. The method essentially relies on empirical, experimental knowledge and still lacks a strong theoretical basis [5].

On the other hand Progress in selective layer-by-layer laser sintering of powders requires more detailed investigation of the laws governing the physical processes that form the basis of the technology. There are several studies regarding the joint mechanisms focused on the heat transfer between the energy source and the metal powder [6, 8–10]. The models that explain the heat transferring mechanism from the skin towards the inner core of the particle as a function of the optical depth penetration, involve a inhomogeneous material due to different heat gradient and heating/cooling rate. But sometimes the tensile strength of a sintered part is higher than that expected for a bulk material. This fact doesn't fit the explained heating model: inhomogeneous material usually has lower tensile strength value than an homogeneous one, the boundary region between an high and low strength zone is a stress concentration area and this causes a decrease of the mechanical performances.

The sintered material shows a clear main anisotropy between the growth direction (z axis) and the plane XY, as well as in this plane the parts sometimes seem to be sensitive to the sintering direction (secondary anisotropy).

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This paper investigates the orientation influence on mechanical performances of Ti6Al4V grade 5 and Cr-Co-Mo specimen built by selective laser sintering. The rupture surface observations allow to explain the tensile strength values obtained as a function of the fine microstructure that is confirmed by metallographic observation.

Table 3 Parameters used for building the DMLS specimens

Laser power	200 W
Laser spot diameter	0.200 mm
Scan speed	up to 7.0 m/s
Building speed	2–20 mm^3/s
Layer thickness	0.020 mm
Protective atmosphere	Max 1.5% oxigen

2 Experimental Procedure

Tensile test specimen were produced by selective laser sintering using Ti6Al4V grade 5 and a Co-Cr-Mo alloy: the alloys composition are shown in Table 1, while mechanical performances of bulk material are shown in Table 2. Tensile test were performed in accordance ASTM E8M specifications (Fig. 1). Standard parameters were used on EOSINT-M270 to fabricate the laser-sintered specimens (Table 3). Every layer is built with the following strategy: the slice area is divided into squares of 4 mm side, built one next to the other. After every square's building the laser spot is realigned. On each layer the laser acts with parallel wipes directed according to a definite scan vector. For the next layer the scan vector is rotated by 25° with respect to the previous one. Figure 2 shows a scheme of the building strategy

In a previous paper the authors showed that the anisotropic behavior may be due to the material distribution rather than to the interaction between energy source and layer [15]. For this reason both of the alloys tested were used to produce specimens that have been built with 3 different orientations (4 for specimens each orientation) in regard to powder deposition plane and laser path (Fig. 3):

- 0° group, specimens' axis parallel to the X direction in the machine building volume;
- 90° group, specimens' axis parallel to the Y direction in the machine building volume;
- 45° group, specimens' axis parallel to the bisector of the X-Y quadrant.

Table 1 Composition of Co-Cr-Mo and Ti6Al4V grade 5 alloys

Co-Cr-Mo	Co	Cr	Mo	Si	Mn	other
	59.5	31.5	5.0	2.0	1.0	1.0

Ti6Al4V grade 5	C	Fe	N_2	O_2	Ti
	<0.08	<0.25	<0..25	<0.2	Bal.
	Al		V		
	5.5–6.7		3.5–4.5		

Specimen density was measured according to the Archimedes principle and the obtained values were compared to the nominal one for each alloy to estimate parts residual porosity. The tensile tests were performed using an elongation speed of 5 mm/min, on SCHENK (HYDROPULS PSB) testing machine, with a load cell acting up to 250 kN.

Results were elaborated through statistical tools and the presence of significant differences between the groups was

Table 2 Physical properties of Ti6Al4V and Co-Cr-Mo alloys

	Ti6Al4V	Co-Cr-Mo
Density (g/cm^3)	4.42	8.8
Melting range °C±15°C	1240–1348	1634–1664
Mean coefficient of thermal expansion 25–300°C, $\times 10^{-6}$	14.3	9.2
Wrought tensile strength (MPa)	938[11]	960[12], 1151–1179[13]
Cast tensile strength (MPa)	896	689[14]

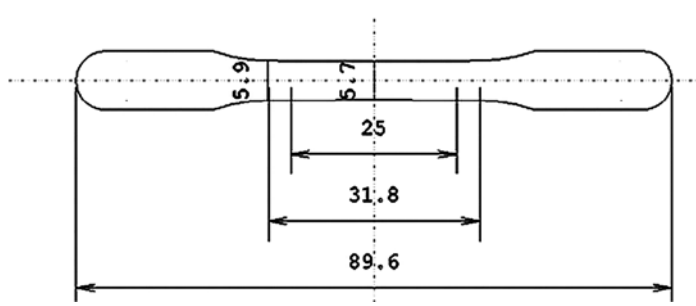

Fig. 1 ASTM E8M specimen size

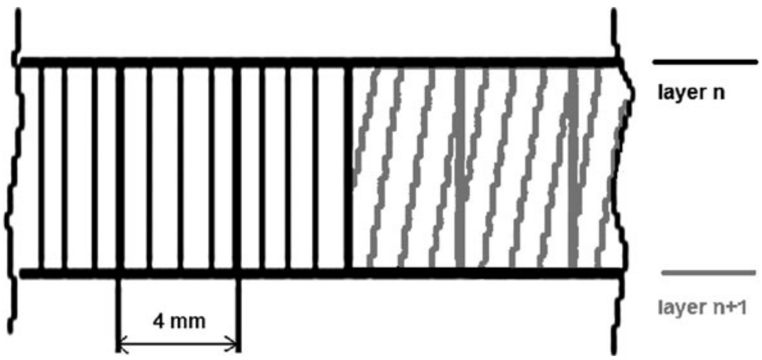

Fig. 2 Laser scanning strategy

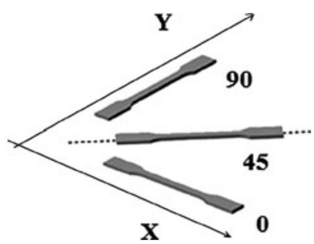

Fig. 3 Built in three orientations with respect to the machine distinctive directions

Table 4 Density mean and standard deviation of specimen with different growth orientation

Specimen density (kg/dm^3)	Mean	SD
TI6Al4V 0°	4.41	0.003
TI6Al4V 45°	4.41	0.020
TI6al4V 90°	4.40	0.020
Co-Cr-Mo 0°	8.60	0.01
Co-Cr-Mo 45°	8.61	0.01
Co-Cr-Mo 90°	8.60	0.06

assessed by the t-test with a level of significance of 0.05. The surfaces of one specimen for each group was metallographically prepared with diamond past up to 1 μm and then, after etching, they were investigated by optical microscope. The Dix-Keller etchant (HF 2% vol, HCl 1.5% vol, HNO_3 2.5% vol; water bal.) was used for the Ti6Al4V while for the Co-Cr-Mo alloy a electrochemical etching (HCl 0.1 M, 2 V, 2 min.), was used. The rupture surfaces were observed by scanning electron microscopy SEM, with integrated energy-dispersive X-ray microanalysis (EDX).

Table 5 Results for ultimate tensile strength and elongation at break

	UTS (MPa) Mean (SD)	ε_b(%) Mean (SD)
Ti6Al4V 0°	1110 (0.57)	12.43 (11.7)
Ti6Al4V 45°	1098 (26.11)	12.60 (0.65)
Ti6Al4V 90°	1080 (6.08)	12.40 (–)
Co-Cr-Mo 0°	1281 (12.80)	12.81 (0.45)
Co-Cr-Mo 45°	1290 (7.91)	14.09 (0.22)
Co-Cr-Mo 90°	1301 (7.64)	13.00 (0.72)

3 Results and Discussion

3.1 Density

For the process parameters used, the Co-Cr-Mo density greatest difference between bulk material and sintered one is about 2.3%; the measured density values are higher than those obtained by hot isostatic pressure [16]. In the case of Titanium alloy this value is 0.47%: therefore the residual porosity is below this value. Density values show an extremely narrow scattering (Table 4).

3.2 Tensile Strength

Mean Ti6Al4V UTS resulted in the range 1080–1110 MPa (Table 5), with elongations of about 12.5%. All groups proved to have good test repeatability with a very low standard deviation. Regarding tensile strength, there is a significant difference (if a significance of 95% is assumed) between group "0" and group "90", even if the difference is of about 30 MPa (Fig. 4). As to Co-Cr-Mo parts, mean UTS was about 1280–1300 MPa, with elongations in the range 12.8–14%. This value is in accordance with literature data regarding the electron beam melting [17]. All groups proved to have good test repeatability with a very low standard deviation. Regarding tensile strength, there are not significant differences between the groups if a significance of 95% is assumed (Fig. 5).

3.3 Microstructure

It is known that the wrought Co-Cr-Mo alloys exhibit superior mechanical and chemical properties compared with the

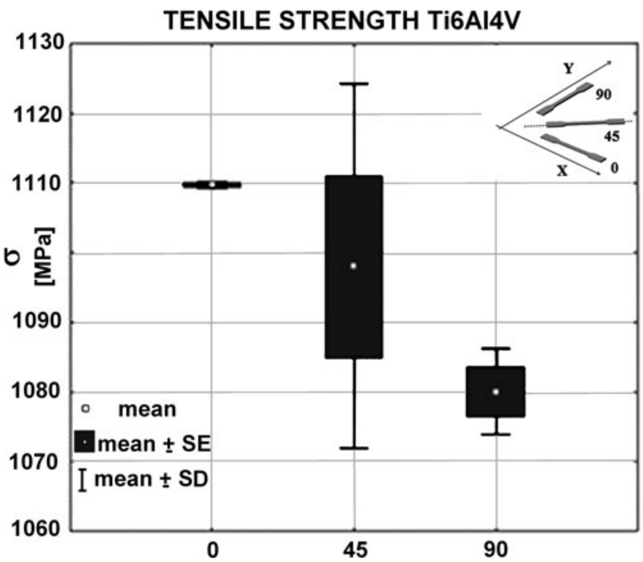

Fig. 4 Box and whiskers diagram showing UTS for the three groups of TI6Al4V specimens

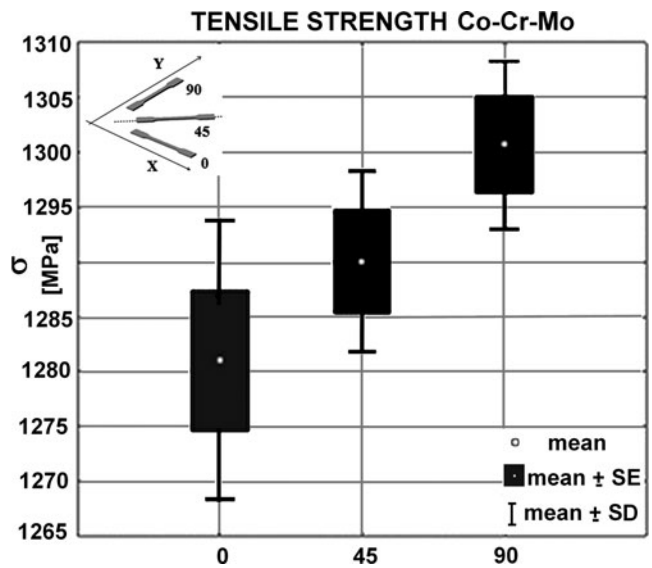

Fig. 5 Box and whiskers diagram showing UTS for the three groups of Co-Cr-Mo specimens

cast alloys due to a finer grain size and more homogenous microstructure [18]. In this research for both of the tested alloys, the tensile strength of selective laser sintered specimens is equal or higher than literature value of wrought part (Fig. 6). This may be due to some composition differences or process parameters [19]. But the metallographic observations suggest that the very fine structure plays an important rule for the mechanical performances obtained. The etched surface of the Cr-Co-Mo specimen is shown in Fig. 7.

Pocket size grains fill structure like droplet, the grains shape and dimension differs from the result of other researcher [20, 18] but it is similar to that which was obtained by selective laser melting using *a* stainless steel 1.4404 [21]. In Fig. 8 the Ti6Al4V microstructure is visible, it matches to a structure quenched from the phase above the beta transus, constitutes the microstructure of the fusion. It differs from the columnar one obtained by some researchers. Columnar formation due to the growth of the grains Countryter to the cooling direction, this leads to directional.

3.4 The Fracture Surface

The fractograph of Ti6AL4V shows a tensile-overload fracture surface of an unnotched specimen. It is a classic example of cup-and-cone fracture having a flat, fibrous central zone (Fig. 9). The fibrous central zone of the fracture surface, showing the equiaxed dimples expected in this region. The dimples are relatively uniform in size, without evident inclusions. Note the numerous small dimples that are situated

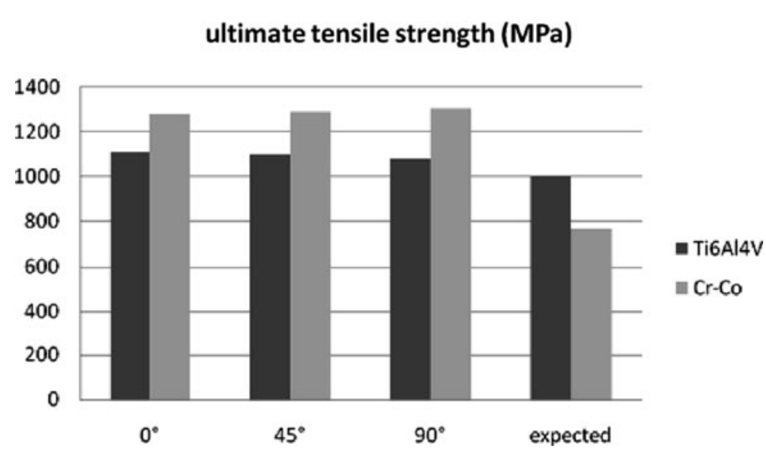

Fig. 6 Comparison between experimental data and literature value

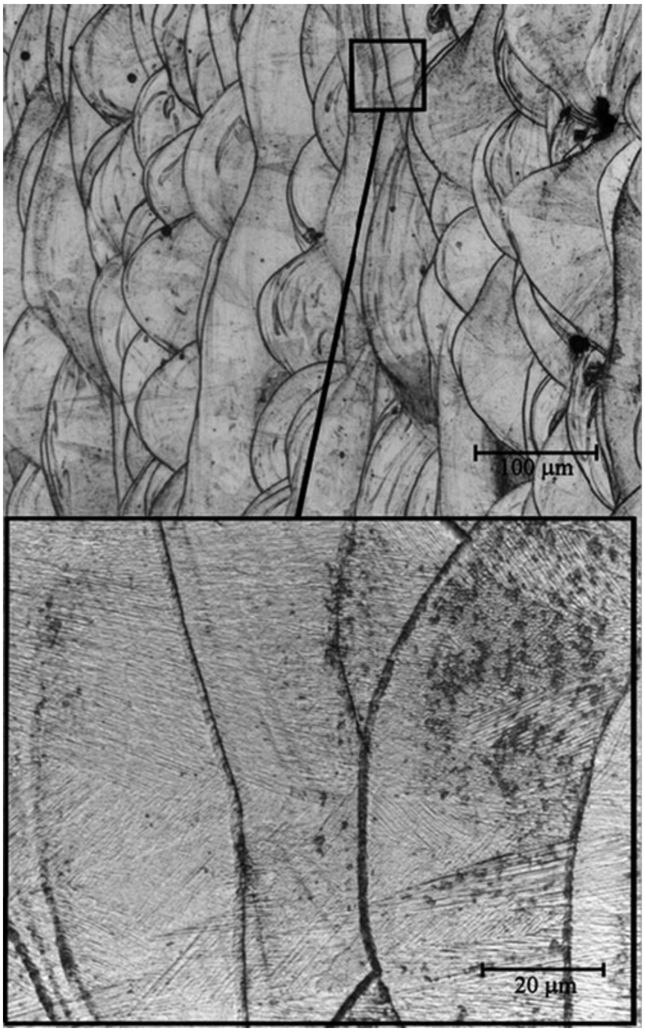

Fig. 7 Co-Cr-Mo – Surface prepared with diamond past up to 1 µm and electrochemical etched

within the larger dimples (Fig. 10). This ductile fracture exhibits no sign of secondary cracking [17].

Some fractures, such as quasi-cleavage and flutes, exhibit a unique appearance but cannot be readily placed within any of the principal fracture modes. Quasi-cleavage exhibits characteristics of both cleavage and plastic deformation. The term quasi-cleavage does not accurately describe the fracture, because it implies that the fracture resembles, but is not, cleavage. The term was coined because, although the central facets of a quasi-cleavage fracture strongly resembled cleavage, their identity as cleavage planes was not established until well after the term had gained widespread acceptance.

The term quasi-cleavage can be used to describe the distinct fracture appearance if one is aware that quasi-cleavage does not represent a separate fracture mode [22]. The fractograph of Co-Cr-Mo shows a quasi–cleavage fracture, in the top-left quarter tear ridges are visible (Fig. 11).

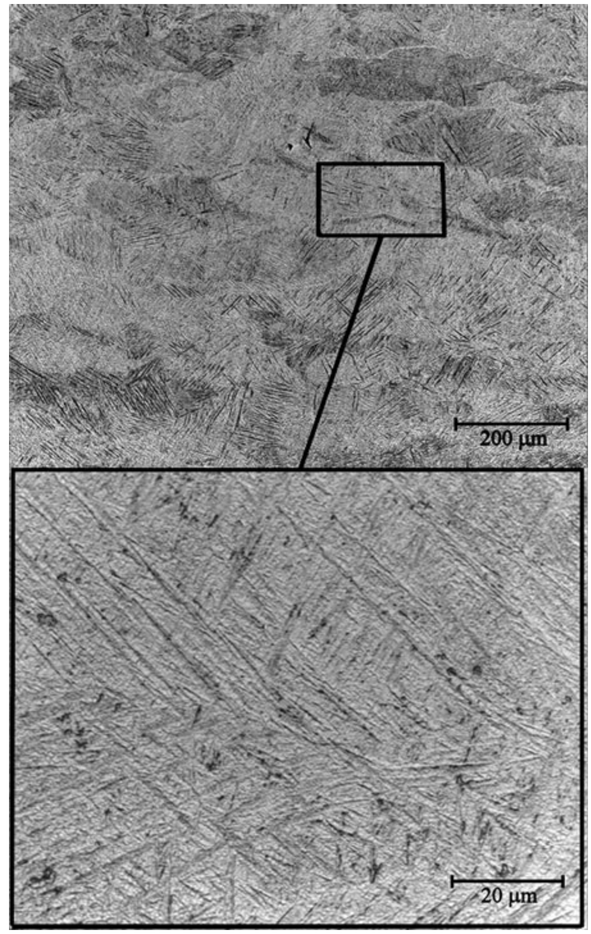

Fig. 8 Ti6AL4V 0° specimen, surface prepared with diamond past up to 1 µm and chemical etched

3.5 Microstructure and Models

From the above results (density value, microstructure, tensile strength) it is possible to affirm that the nucleation and the cooling rate play important roles in the particle joint mechanisms and determine the fine structure and mechanical performances of these dental alloys. The development additive manufacturing models take in acCountryt the interaction between energy source and material adsorption but they cannot explain completely the performances of the part. For example with liquid phase sintering mechanism, complete elimination of the porosity is generally not possible because repulsion forces arise between particles at a high fraction of the binding liquid component [20].

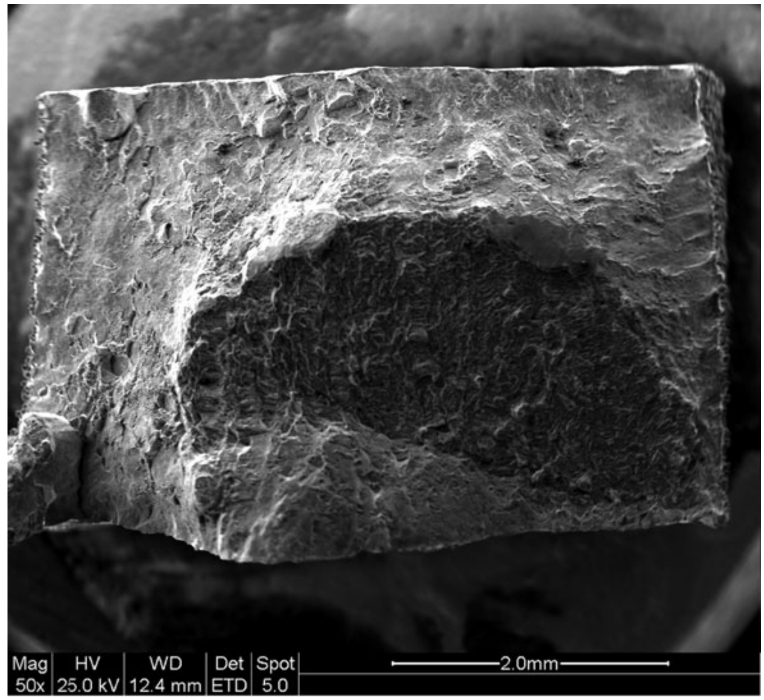

Fig. 9 Ti6Al4V 0° specimen, cup-and-cone fracture surface due to a tensile-overload

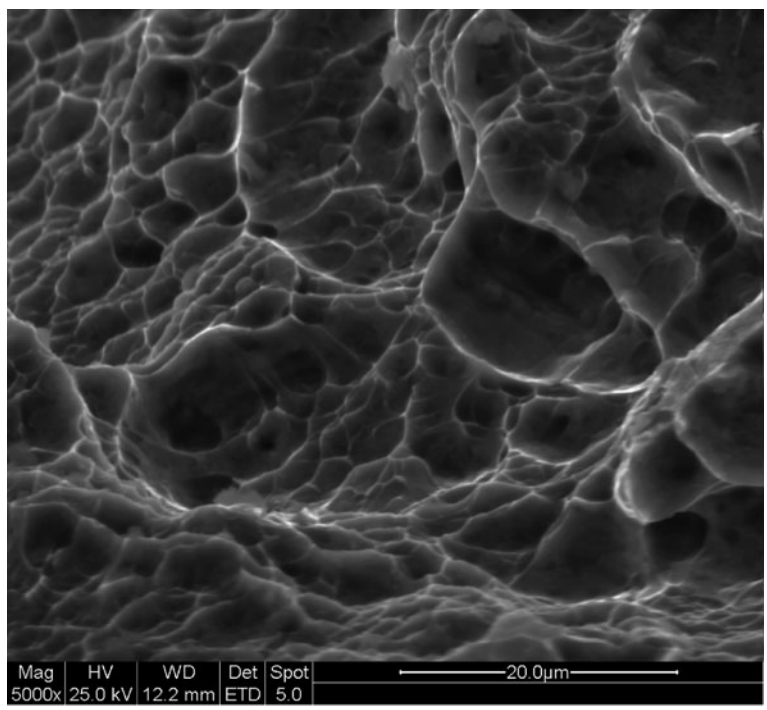

Fig. 10 Ti6Al4V 0° specimen the dimples are relatively uniform in size, without evident inclusions. This ductile fracture exhibits no sign of secondary cracking

4 Conclusions

- Using the described laser path strategy, the mechanical performances of the parts are unsensible to the part orientation.
- The tensile strength of the two tested alloys are equal or higher than those reported in literature for part produced by hot isostatic pressure and electron beam melting.
- For both of the tested alloys it is possible to believe that the mechanical performances are due to the fine microstructure.

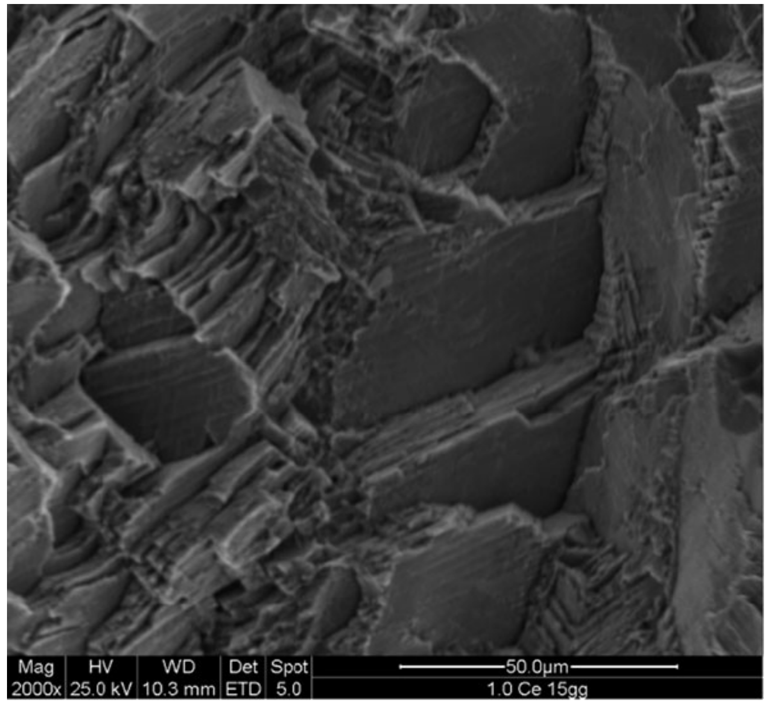

Fig. 11 Co-Cr-Mo 0° specimen, quasi-cleavage fractures, tear ridges are visible

- The nucleation and the cooling rate must be considered in a process model to explain the fine structure.
- The fractograph of Ti6AL4V shows a cup-and-cone fracture; in the central zone of the fracture surface there are equiaxed dimples, This ductile fracture exhibits no sign of secondary cracking.
- The fractograph of Co-Cr-Mo alloy shows a quasi–cleavage fracture. Quasi-cleavage exhibits characteristics of both cleavage and plastic deformation.

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