Frank-Lothar Krause
Editor

The Future of Product Development

Proceedings of the 17th CIRP Design Conference

CIRP

BERLINER KREIS
Wissenschaftliches Forum für Produktentwicklung e.V.

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With 298 Figures and 22 Tables

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Editor

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Preface

Product development is changing since its early beginnings. Especially since the time of industrialization the speed of this change has constantly grown. The 1960 saw the introduction of computers into product development. The development of computers and software are amazing artefacts. Product development methods have been generated for the use in teaching as well as for the use in industrial processes. Most of the methods have been created without the usage of computers. That means that even today conventional methods are still dominating and large numbers of tools and systems are used for the support of product development processes. However, still missing are methods of computer integrated product development.

»The Future of Product Development« comprises 68 papers from more than 20 countries. It is a collection of current industrial views and of research results. Three major industrial companies outline their demand for better product development, followed by the major vendors in the field giving their reply. The remainder are papers on current RTD.

The conference can be seen as a mirror of international tendencies in product development in the year 2007. It shows the urgent need for change in product development and for new solutions. The presentations in this conference are therefore of direct help for the industry and stimuli for ongoing discussions on enhanced product development. In this sense the presentations and the connected discussions are in turn initiating new research.

Despite its complexity the program is very much focused. Without the activity of the international program committee the conference program never could have been assembled. The merits for content and quality of the papers belong to them only.

Without the sponsors the whole approach, including the industrial and scientific exhibition as well as the large number of talks would not have been possible. Our grateful thanks go to all of them.

CIRP, the International Academy of Production Engineering has a long tradition in conducting Design Conferences. It is a great pleasure and obligation that Berlin was chosen for the 17th CIRP Design Conference. For the first time the conference was jointly promoted by CIRP and the Berliner Kreis – Wissenschaftliches Forum für Produktentwicklung e.V. (scientific forum for product development, a group of german speaking professors working in the field of product development). This co-operation is a unique opportunity to exchange experiences and ideas between industry and academia.

The proceedings give a very precise overview about the state of the art and ongoing changes in product development. We hope that they are of help for the industry as well as for research and teaching.

For all their special encouragement and help I would like to thank my chief engineers Helmut Jansen, Christian Kind and Uwe Rothenburg and the members of my group.

I thank the publisher as well as the typesetting and image editing team for their creative support in preparing the proceedings for print.

Berlin, March 2007
Frank-Lothar Krause

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PDM/ EDM as Integration Layer for Continous Workflows Based on Relevant Product Data

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PDM and PLM are presently being widely discussed in the automotive industry. The car manufacturers demonstrate quite different technological approaches and advances. Nevertheless, the practical implementation is often insufficient.

Following several successful pilot projects at the Volkswagen Group, last year a start was made with the complete conceptual planning of a Group-wide implementation of a PDM/EDM program. The growing demands in regard to product range, shortened development cycles and increased efficiency have led to changes in the organisation. Last year Volkswagen began with the successful restructuring of the organisation including the introduction of vehicle-based business management, "project houses" (Projekthäuser) and so on.

In order to holistically fulfil the set goals in the Group, work processes had to be further adapted from a vertical to a horizontal structure. This is possible only in conjunction with substantially greater digitalisation and virtualisation. In order to do justice to the future demands in all segments of the process, it was necessary to introduce integrated Product Data Management (PDM) throughout the entire Volkswagen Group. PDM ensures integrated work processes with the respectively relevant product data throughout the entire product life cycle from design to development, production, sales, after sales all the way to recycling.

The introduction of PDM resulted in three main points of implementation for Volkswagen:

1. Further development of the work processes
   Optimisation of work processes throughout the product life cycle for the brands and model families in the Group.
2. Integration of the required product data
   Adapted to the new process, the required data are made available to the respective target groups (designers, prototype builders and so on) via integrated workplaces.
3. Disentanglement and simplification of the IT system structures
   In the course of preparing data for specific target groups, the existing IT system structures will be examined. Systems which are no longer required will be retired and the important systems will be integrated as far as technically possible.

DMU@Airbus – Evolution of the Digital Mock-up (DMU) at Airbus to the Centre of Aircraft Development

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Abstract
The Digital Mock-up within Airbus has emerged from discrete applications to full 3D Aircraft design and development. Since the late 1990s programmes like A340-500/600, A380 and A400M have paved the way for integrated DMU operations across Airbus and its supply chain.
One cornerstone detailed herein is the Product Structure. It is vital for concurrent distributed collaboration with the Configured DMU and draws on dedicated views on the Aircraft to satisfy individual disciplines' requirements for ways of working. Another crucial element is DMU operations over the Extended Enterprise (=Airbus plus partners and suppliers). It ensures that everybody can work with latest, complete and configured Digital Mock-up data.

Keywords
Configured Digital Mock-up (CDMU), Product Structure, Data Exchange, Extended Enterprise

1 Introduction

This numbers denote that the amount of reduction in the variability of response obtained by using regressor variables is about 97 % and it is about 93 %, if it takes the number of regressor variables into account. Furthermore, the sensitivity analysis is carried out in order to assess which input variables are the important factors in affecting the variability of each response as well as the overall desirability function. Additionally, this information is also useful in understanding which inputs are the limiting factors in the response variability and which efforts should be carried out in reducing the variability. By carrying out the t-test which compares the estimate value of each factor with its associated standard deviation to result in the t-ratio, the significant factors can be determined. Those are the process lead time, the resource number and the interaction between both factors. They have significant high values of t-ratio. They also have significant less probability of getting greater t-ratio than 0.05 (probability of significant level) which means rejecting the hypothesis that the parameter is not significant in the model.

Functional verification of landing gears. The Digital Mock-up was then used only selectively in everyday design. Stringent aerospace requirements and insufficient IS/IT hardware and software performance ruled out – for the time being - 3D CAD to be applied on a larger scale.

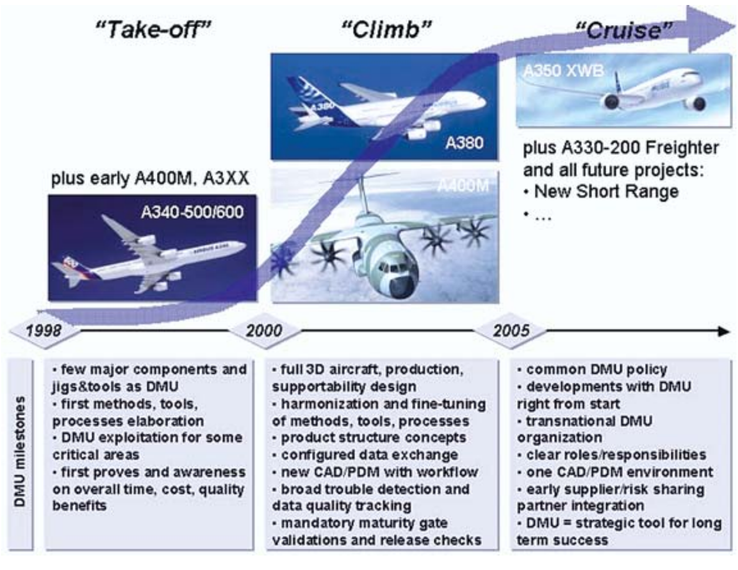

Fig. 1: Three phases of Digital Mock-up developments in Airbus

That changed in the second half of the 1990s. Feasibility studies and early concept design for A3XX (later named A380) and the military transport aircraft A400M already started in 3D. But it was the launch of the A340-500/600 Programme (long range derivatives of the basic A340 aircraft) that proved the advantages of a DMU for major components: it were both a business decision for keeping budget and schedule as well as higher IS/IT performance that were decisive in 1998 for going for a Digital Mock-up as complete substitute of Hardware Mock-ups. This wasn't done for the whole Aircraft though, but for assembly/integration critical areas.

Full-scale developments of A380 and A400M then broadened the knowledge base tremendously on how to create, exploit and manage the DMU. It was the time of "climbing" to new heights of developmental sophistication. It laid a solid foundation for latest Aircraft programme launches such as the A350.

The Configured Digital Mock-up (CDMU)

The definition of the DMU in Airbus is shown in figure 2:

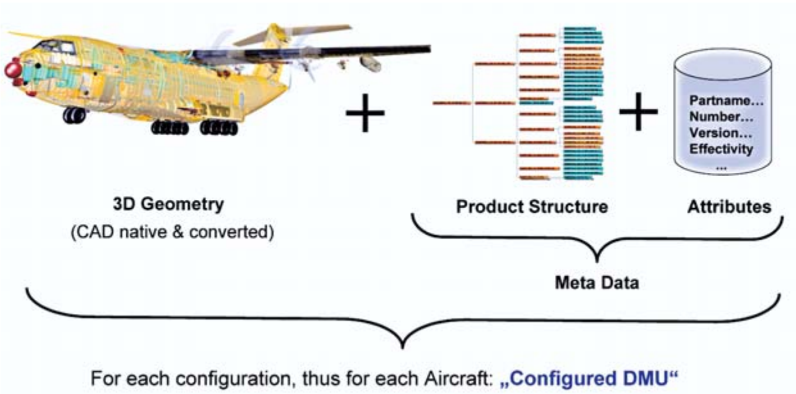

Fig. 2: Definition of the Configured Digital Mock-up at Airbus

The Configured DMU is more than a digital replica of a single Aircraft: each customer configuration, each study or investigational scenario is retrievable from the database. This is made possible by a sophisticated effectivity management based on relatively few configuration attributes. It is the basis for distributed concurrent engineering of both heavily customized products for the operators and parallel development of an aircraft family (e.g. passenger and freighter versions, stretched and shortened versions).

From an organizational point of view, DMU specific work commenced locally in Design-Build Teams, when a few designers started focusing more on issues like product structure handling, data exchange, trouble detection and visualization support during reviews. With new programmes that community grew fast. The job of the "DMU Integrator" began to emerge, with dedicated tasks, individual roles and new responsibilities. Realizing their key role for enabling concurrent creation and exploitation of the CDMU the DMU

Integrators from all four Airbus national companies are now being bundled in a single transnational organization. That enables harmonizing the ways of working with the DMU, leverages knowledge transfer across programmes and draws on synergies of core competencies beyond national borders.

Two crucial elements of DMU helping to meet the challenging objectives are explained on the following pages: the Product Structure and DMU operations across the Extended Enterprise.

This paper focuses on the product DMU itself, hence the Aircraft. There are, of course, other DMUs as well: e.g. 3D jigs and tools, production- and transportation facilities that usually fall under the "Digital Factory" realm, or DMU test benches and operative equipment that is developed and verified by the Supportability community.

2 Selective Cornerstones of DMU Development

2.1 The Product Structure

If the CDMU is the basis for 3D design activities, the product structure is its very heart. It is more than merely a "simple" breakdown of the Aircraft, and it is more than a drawing tree. In Airbus, the product structure is an *organized collection of business and technical information* related to the Aircraft. It not only takes into account the hundreds of thousands of parts that constitute the Aircraft itself. It is also the result of careful considerations concerning work-sharing, industrial flow, regulations of authorities, change process and configuration management as well as multiple requirements documents.

The product structure concepts were elaborated in the wake of A380 and A400M projects. The aim was to develop and implement standardized and transnationally harmonized rules how to best organize data and information, giving different disciplines their points of view on the product they prefer most for design and development. Thereby the visibility of the DMU in either view, customization and parallel working had to be ensured.

Data and information can be accessed in several *views*. These views arrange the data differently in very specific breakdowns, depending on priorities. Hence, the same item may belong to a contractual function, a design function, to an assembly or to a maintenance task. In everyday design the product structure is a working tool for thousands of engineers.

The two most dominant product structure breakdowns are the

- *Functional breakdown*; this is basically the point of view Engineering has on the aircraft. It decomposes the aircraft functionally top-down to major components, sections, zones, assemblies, sub-assemblies and to the single parts themselves.
- *Manufacturing breakdown*; it is the manifestation of how the Aircraft is assembled, in fact the bottom-up approach, from single parts to assemblies, sections and further up.

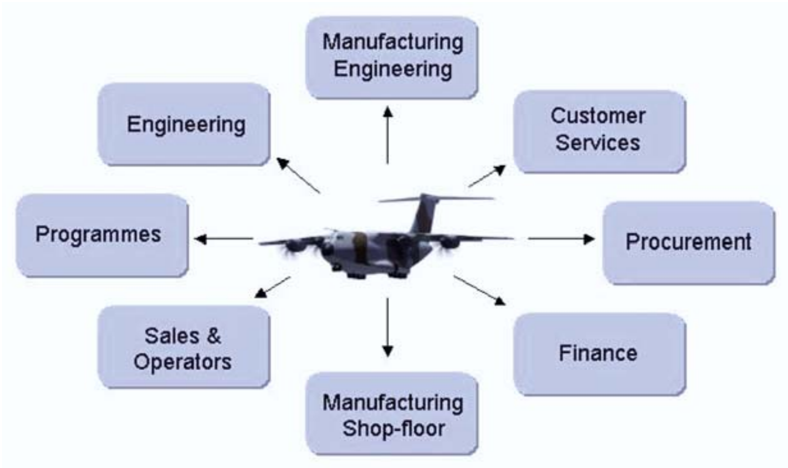

Fig. 3: Different disciplines extract their views from the Aircraft

For daily CDMU operations, three views have emerged as the most relevant ones; they are presented in figure 4 below:

The so-called *As-Defined* view is the major CDMU breakdown in the early phases of design. It organizes all different kinds of auxiliary models that are necessary for design trade offs: space allocation models of structures, systems and equipments, interface models, master geometry (loft and major reference planes and axis) and layout models. Till the end of Definition Phase these models are validated through maturity gates. Once sufficiently defined they remain in a “frozen” status. While design engineers converge to the best trade-off, manufacturing engineers can start elaborating the best built-concept based on As-Defined data. That takes place without interfering with the Engineering-preferred breakdown.

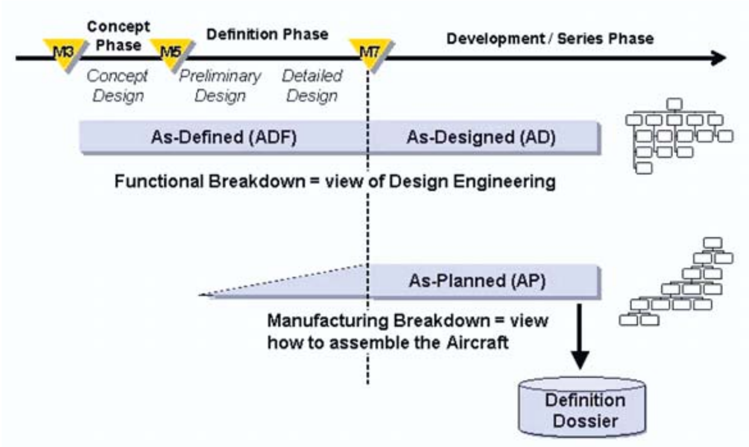

Fig. 4: Most relevant product structure views of the CDMU

The *As-Designed* view is the successor of the As-Defined in the Development and Series Phases, but made up exclusively of definition models which are then officially released via the PDM system.

Both functional views are organized in three areas:

- The *Upper Level*; it decomposes the aircraft top-down via six levels. It reflects aircraft family planning, typical Airbus work-sharing components, Airbus Aircraft sectioning and the international ATA classification (ATA=Airline Transport Association of America).
- The *Configuration Level*; this layer is made up of Configuration Items (CI), which reflect a specific function of the aircraft and the Link Object (LO) the holder of the configuration information.
- CIs are actually "management points" where it is decided which technical solution is taken for satisfying a given requirement.
- The *Design Level*; that's the area where design takes place and where the Aircraft is detailed down to the very single parts. The top assembly is called Design Solution (DS), which actually is the technical solution for a requirement. There can be several DS below one CI reflecting different ways satisfying the requirement: e.g. a metal Flap, a carbon fiber Flap and a hybrid Flap are evaluated during trade-off studies. One will finally be chosen as baseline solution for further detailed design.

The unique identification what finally will be built into an aircraft is the LO-DS pair: it defines what technical solution is taken (DS) for what types and/or ranges of Aircraft (e.g. what customer versions). Between As-Defined and As-Designed there is a so-called *transition* phase: it ensures that auxiliary models and final development data coexist during a certain period of time to ensure a consistent and complete CDMU while being able to track which data are migrated to the next phase.

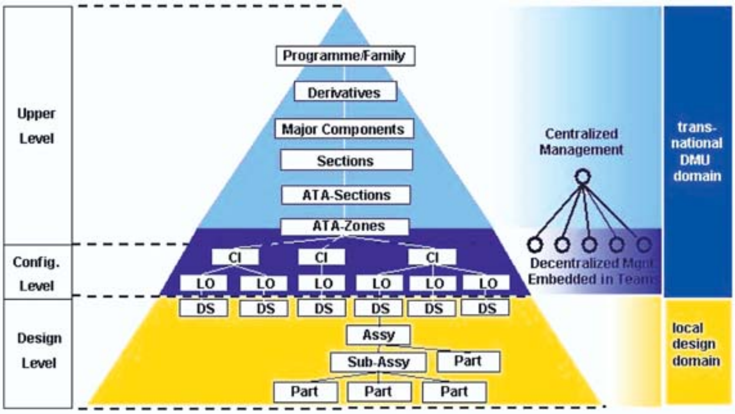

Fig. 5: Functional Product Structure breakdown

The very same CDMU in Development and Series Phases is shared by two views contemporarily: the As-Designed and the so-called *As-Planned* view. 3D geometry is the same, just the product structure breakdown - hence the view - is different. That is why data are also called "*ADAP-*" CI/LO/DS/assemblies/parts, indicating their belonging to both views. The As-Planned view is the unique input from all product structure views to the official *Definition Dossier* (the collection of all relevant data that in the end define the Aircraft – 3D models, drawing sets, Engineering Change Notes, standards and processes specifications, bill-of-materials). The Definition Dossier itself is the input for the Manufacturing-, Inspection and Maintenance Dossiers – the documentation necessary to produce, service and operate the Aircraft.

The management of the product structure takes place centrally for the Upper Level. This ensures high quality and consistency of the breakdown for all distributed design teams. The Configuration Level is managed locally by DMU Integrators who work co-located in multidisciplinary teams. They ensure the breakdown to reflect design team requirements, the linking to the global CDMU and the visibility of the actual 3D design status. As both levels are managed organizationally under one transnational roof has several advantages: new rules and updates are implemented quickly and consistently company-wide and the CDMU is useable for all disciplines as it is based on agreed schemes.

2.2 DMU Operations over the Extended Enterprise

As it is with the aerospace business as a whole, large aircraft design and development too has become a very global endeavor itself.

Fig. 6: Airbus global distribution and diversity (as of November 2005)

From a DMU point of view that means that wherever and whenever designers may work, they will need to share relevant data and information on a near real time basis, as do their colleagues in Toulouse, Hamburg, Bremen, Filton or Getafe. The goal is being able to “design-in-geometrical-context” with complete, up-to-date, consistent and configured environment geometry and interface models. Therefore, data exchange and data sharing have become the “fuel in the pipes” of concurrent engineering.

The requirement calls for life cycle handling of high volumes of data, with considerable frequencies of exchanges and management of iterations. In Airbus Germany in 2005, in the A380 project alone, the average volume of DMU data exchanged internally with other Airbus sites ranged between 80 and 140 GByte per month, and exchanges with suppliers ranged from 50 to 90 GByte. Furthermore, closer and earlier integration of suppliers and risk sharing partners has put high emphasis on questions of interoperability of tools and systems. Once these new participants are on board design activities must see a fast ramp-up. Communicating a common DMU policy and flexibility on both sides solving everyday operational issues have turned out to be crucial elements for success.

In particular, the A380 programme is marked by a highly heterogeneous tool environment, adding further complexity to the most challenging Aircraft development project in the history of Airbus. 3 different 3D CAD systems, 2 assembly management tools and 4 different (mostly legacy) PDM systems within Airbus alone accounted for a great deal of operational DMU shortfalls. Design-in-geometrical-context was hampered by missing, outdated or flawed (e.g. through erroneous conversions) 3D models and meta data. That is why considerable efforts were laid in solving those issues and ensuring regular configured data exchanges internally as well as from and to suppliers.

At the end of Concept Phase the Airbus partners in the A400M programme switched to a new and common 3D CAD tool and a single new web-based PDM system. It eliminated many of the issues A380 had to face. This strategic step has not been followed though by all risk sharing partners. Also the architectural set up with four separate PDM instances resulted in synchronization problems among them. It forces to remedy a temporarily inconsistent CDMU while still having to handle a considerable number of data exchange transactions.

A350 actually benefits from experiences in both mentioned programmes. It uses the same CAD/PDM tool set as A400M as well as most of its methods and processes. But it bypasses potential shortfalls by working with a single-instance architecture and the strategic approach of ensuring smooth interoperability with risk sharing partners and suppliers.

Lessons Learned

Some of the lessons learned for DMU operations point right to be beginning of partnership: during the bidding process it is important to evaluate the best overall offer, not the cheapest. Suppliers and risk sharing partners must be able to cope with the fast pace of CDMU evolutions. They must know what to expect while Airbus taking a strong lead in ensuring their smooth synchronization with internal processes. This can best be done by going from classical data exchange to data sharing.

The transnational DMU organization has been established to be both the driver in enforcing, tracking and monitoring a high quality CDMU as well as its enabler for the multitude of departments over the entire Extended Enterprise. In the end, everybody is a little bit more interwoven with each other. But this is one important answer to ever-stronger market pressures. It does pay off, for both sides.

3 Steps into the Future

Near and mid term priorities are ensuring successful entry-into-service of the A380 and A400M. The DMU remains to be one of the crucial elements for dealing with development, customization and integration complexities in these two major programmes.

Recent troubles urged Airbus to launch the "Power 8" recovery programme. One of its key initiatives is to find ways to develop Aircraft faster. This is the focus of the "Development and Ramp-up Excellence – DARE" project. It aims for three things: (1) an integrated planning, (2) early involvement of the supply chain and (3) a common digital product model across the entire Extended Enterprise. This underlines the strategic importance of DMU for Aircraft development. The A350 XWB (XWB stands for "Extra Wide Body") is actually the first major new development programme that will benefit from that approach.

Another project is to prepare for pure digital 3D development. It aims at eliminating – as much as possible – 2D drawings from the design and manufacturing processes. This will further enhance reactivity and cut costs and time. It shall, in the end, close the remaining gaps between Engineering and Manufacturing and unite their distinctive 3D worlds to a common virtual development space.

4 Conclusion

The last years have seen four major Airbus programmes being launched in relatively short sequence. Given the long development cycles of large transport aircraft this is a remarkable fact: it provided the unique opportunity to apply lessons learned of the new DMU discipline from one programme to the next almost without delay. The frontiers of DMU operations were pushed fast and relentlessly for reaping the full benefits of 3D development. But this came not for free, let alone guaranteed success, just by going 3D. It was the cumulated effort of a great many people that placed it in the centre of development. Only recently the Digital Mock-up Integration was acknowledged as one of Airbus' core competencies for successful Aircraft development. Having gained all that experience working with and managing the DMU we have reached our "cruise" altitude. The challenge now is to travel the long distances as effectively and as efficiently as possible, probably climbing to even higher levels along the way.

Knowledge-based Design – An Integrated Approach

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[3] protics GmbH, subsidiary of DaimlerChrysler, Division of Product Data Management, Stuttgart, Germany

Abstract
The dependency between products and processes in today's high-tech domains is very complex, and the resulting interrelations are difficult for the individual engineer to manage. This paper presents a methodological concept (templates) that standardizes the design process and its downstream processes. The results of an accompanying psychological user acceptance study are also presented and discussed.

Keywords
Design of Experiment, Product Development Process, Process Analysis, Process Optimization

1 Introduction

From a strategic viewpoint, the automotive market is a market in the endgame. This means that the market has over productivity of products and the differences are decreasing between the various automotive companies. Especially for the premium automotive manufacturers, it will be increasingly difficult to distinguish new innovation from the other automotive competitors. For this reason, the Mercedes Group formulated a strategy in the 1990s to rapidly expand its model range. In 1983, the C-Class had one car body, four engines, and one factory. In 1993, the range increased to four car bodies, seven engines, four design lines, and two factories, and by 2000, the C-class had five car bodies, seven engines, three design lines and four factories.

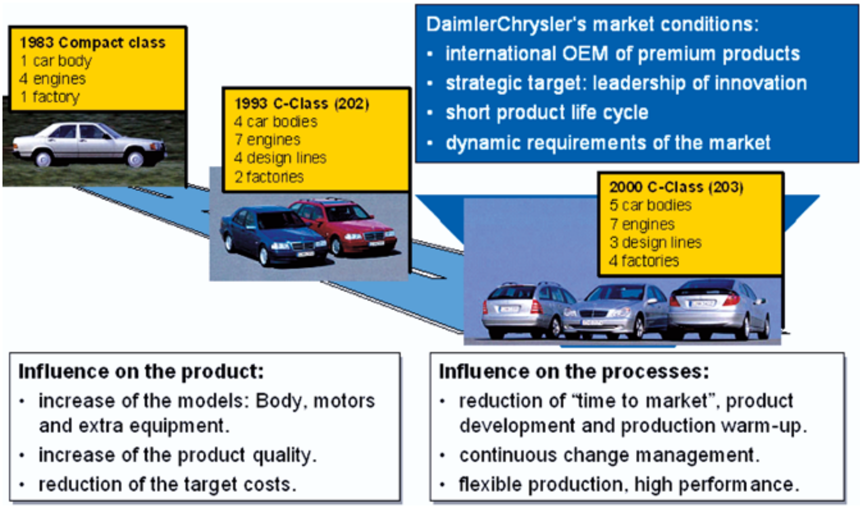

Fig. 1: Historical model of diversification of the Mercedes C-Class

The increase of model range required worldwide production in collaboration with other companies. The international merger is one way to generate an increase in production that is profitable. But this was not the only change. The features of the car changed dramatically, too. Electric, electronics, and software had a massive influx in the former mechanical-dominated automotive world. The result today is a higher degree of complexity in product, as well as in design and engineering processes. To handle the increasing complexity, the automotive companies implemented the digitalization of product development and the optimization of processes in the mid-1980s.

The investment in engineering increased proportionally with the extent of model range, whereas the amount of employees per model decreased. New IT systems and methods as well as changes in product development processes made this possible. One example of automation is the introduction of CAD systems, which were implemented to increase productivity and product quality, while reducing developmental effort. [1]

Despite these advances, the accelerated market trends resulted in increased quality problems at the beginning of this millennium. Entire industries moved into a period of consolidation that was characterized by high discipline of cost and process. Rapid innovations supported these bench-marks. Examples for this development are digital control of the highest degree and processes of immanent quality, digital prototypes, frontloading, digital factories, and integrated product data management.

To understand this trend, it is essential to realize that innovative products need innovative product development processes. These process innovations are often IT-driven. An important innovation is the topic of this paper, knowledge-based development with templates.

Templates as knowledge-based applications are a comprehensive approach for archiving and managing all essential information in a standardized product and process description.

The future of the automobile industry will bring new challenges that require such solutions. The results of a comprehensive study [2] predict for the automotive industry that three things will characterize the future:

1. A gap between high expectations and low prices.
2. Product consisting of "silicon and steel" and
3. Change of structure of creation of value. The first point means that we have a gap between the high expectations of customers regarding innovation and the reluctance to pay corresponding prices.

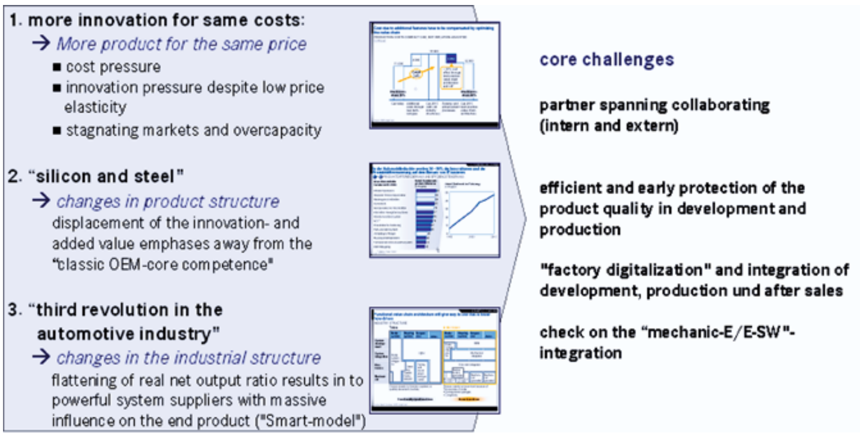

Fig. 2: Future trends in the automobile industry

This combination of trends increases cost and process pressures and intensifies competition. The proportion of electric, electronic, and software components in the automobile will continue to increase. The classic competence that OEMs enjoyed during the previous century will decrease, and consequently the OEMs' portion of the creation of value will decrease. OEMs will have to integrate many suppliers. The structure of the industry will change and perhaps will make history as "the third revolution of the automotive industry".

Several solutions have emerged to meet these challenges. The automobile companies are working on integrating the development processes for mechanical, electric, electronic, and software, as well as on the down stream of process chain, inclusive companies of partner integration, global collaboration, and multi-discipline optimization. In particular, knowledge-based development is an important approach for handling the challenges.

But the technical side of templates is not the only important factor for successful introduction. Human beings, as a significant economic resource, as well as issues about their cultural differences, are frequently forgotten. This oversight makes the introduction of new technical systems more difficult. However, when human thinking and behaviour, as well as cultural aspects, are taken into account, the implementation of such processes not only increases motivation but also helps to anticipate and reduce potential barriers.

2 Engineering Templates

2.1 Template Classification

Templates as knowledge-based applications are a comprehensive approach for archiving and managing all essential information in a standardized product and process description.

Each car line, each assembly, each component contains various and numerous characteristics that require dedicated development steps. From conceptual design, through all design stages to data archiving, sophisticated development methods and IT solutions must be employed. Seamless and just-in-time information for all downstream processes and an unambiguous and easily performable process definition are assumed. Using template technologies is the key to handling most of these aspects in a modern CAD system. The schema in Figure 3 shows the correspondence between external factors and the specific template-based design stages. Increasing content within the four template extensions can be distinguished. The level of detail increases as it moves from the outer shell to the centre. **Function templates** contain only rough geometrical information and are mainly used for providing the main dimensions and specification values. Application of **concept templates** includes the main characteristics of vehicle models like sedan, convertible, station wagon, or SUV. They are the foundation for best practice design concepts. The digital validation of functional principles is the task of **study templates**. The detailing of such a validated concept leading to a full geometrical description of parts, including relevant information for manufacturing and final assembly, can be done in **part templates**. Within all layers, the design engineer can use specific templates for the different modules of a vehicle.

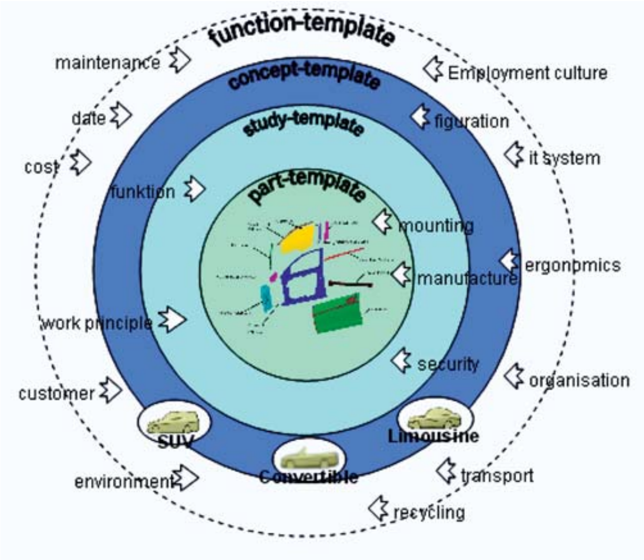

Fig. 3: Requirements for a template-based product description

A tight collaboration between DaimlerChrysler Group Research and Mercedes Car Group Development facilitated the development of the methodical foundations first implemented in the body in white, powertrain and chassis design domains. The outcome of this study was published at the 2005 DaimlerChrysler EDM Forum in Stuttgart [3].

2.2 Link Management

To provide the opportunity to include all geometrical and non-geometrical information independent from the process step, a specific PDM archiving concept was developed. It enables data retrieval with different points of view. A generic information structure, independent of the level of detail, is the basis for the archiving of all templates.

This structure is a summary of different information aspects of a comprehensive product description. Depending on the concrete development task, the necessary information is activated and shown in the expected context. The structure distinguishes between parts with product part number and so-called arrangement (support elements). The generic information set creates the structure for all input data for the templates and links all underlying datasets existing in the PDM database to the part description.

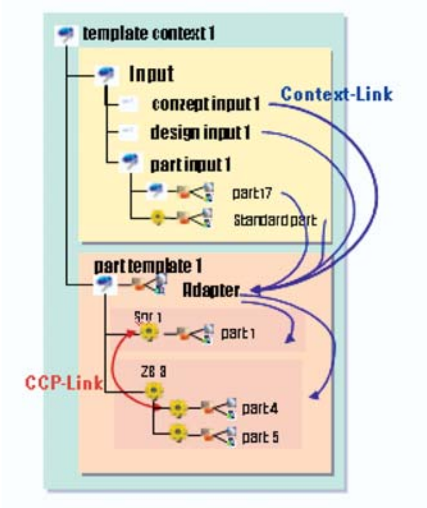

Fig. 4: Concept template technology at DaimlerChrysler

Only a suitable PDM solution can ensure such a dynamic information flow. The sophistication of CAD functions requires a higher level of PDM capability. A real, valuable benefit can be achieved only through the integration of CAD and PDM. In addition to the known PDM requirements, such as configuration management, versioning, and release and change management, the capability to administer constraints and so-called "multi-model links" is essential. This means especially the constraints between geometrical elements and parameters within parts as well as constraints between parts and subassemblies. More than 2,500 links are needed to define an entire body-in-white structure within a concept template [3]. This link management generates the capability of dividing complex structures into template-based and usable part structures. Without this capability, it would be impossible to share the complete information and knowledge of a multi-part assembly among numerous design engineers.

The mandatory use of template-based design processes leads to a continuous improvement of the design maturity, from the early phase down to detail design, and prevents endless iteration. The reuse of these approaches depends on the degree of flexibility and adaptability of the predefined templates. The predefinition, by using knowledge-based form and function features, facilitates this reusability. These feature applications are not only part of detail design; they can also define and mutate conceptual structures through an internal protection structure.

Using knowledge-based templates is an appropriate approach for integrating proven concepts or systems into a new product design. They contain all the information necessary to define the technical behavior in a general context. The disadvantage of this approach is obviously the intensive effort needed to define and maintain a universal template concept that considers all potential variants of future design instances.

To succeed in the development and deployment of such a sophisticated concept, technical and conceptual aspects must be considered. The most important part of the game is the human being – the engineers and designers who have to perform this new process and methods.

3 Psychological Aspects of Template based Engineering

The common definition of working systems has already been described in the human-technique-organization approach. The working system consists of social and technical substructures. Humans, technology, and organization are interdependent and interacting components. The task is the center of the working system [4]. The interaction between the substructures has also been described [5]. All components for solving the working requirements are known.

The previous discussion of the templates focused mainly on technical design with the purpose of process optimization. However, human, organizational, and cultural factors should also be considered. In the following, human factors are considered to ensure a successful introduction of templates and, therefore, a standardization of the process. The cultural aspects and the organizational aspects, which also have a strong impact on working systems, are only mentioned in this context.

Early integration of the user is the best way to consider human requirements in time. Disadvantages of the previous process and aims of the new process have to be presented. When developing templates the integration of the user supports the acceptance of the new technology and prevents un-necessary concerns because the designer's thinking and behavior are considered [6].

A failure to consider the designer's thinking and behavior when solving a design task results in a mental workload which decreases the acceptance of templates. Constructional defects and motivation loss may lead to financial penalties. Therefore, a cognitive ergonomic design of templates is also important when considering financial aspects.

At DaimlerChrysler AG, a study was conducted to analyze critical incidents when using templates. Based on the results of this study, improvements for the design of templates were conducted. In the study, two different construction elements were compared. One construction element was composed without features and then was composed with features. In total, six designers participated in the study and were subjected to the experimental conditions. For reasons of comparability, participants were constrained by means of pre-assigned variables to the experimental conditions. In the first part of the study, the participants had to redesign a construction element (adaptation construction) whereas in the second part of the study a further adaptation construction had to be made. The participants who solved the first task with the feature solved the second task without the feature. Participants who solved the first task without the feature at the beginning of the experiment solved the second task with the feature accordingly. Therefore, each participant worked with both terms of the experiment. Initial results indicate that the construction element with features was estimated differently depending on CATIA V5 Engineering expertise. Persons with low CATIA V5 Engineering expertise considered the implementation of a construction element with features as less effective. The shorter design time and the faster creation of geometries were seen as an advantage whereas the loss of the overview and the complexity of the design element because of the strong structure were seen as a disadvantage. The design time was different depending on the type of template and the design task. The persons who had used the construction element with features solved the more complex design task faster in terms of the design time, whereas in the construction of the less complex design task, the group without features was faster. The visual analysis of the videotaped design process will provide further information about critical incidents and their solutions. Additionally, in the second part of the study, the handling of information about multi-model links was analyzed – the engineer should identify all multi-model links. All participants took advantage of the possibility of quickly changing with the multi-model links. However, they also criticized the loss of the overview of the existing coherences. Considering that the body shell model has more than 2,500 multi-model links which are not directly visible in the CAD system, some thought must be given to alternative solutions. The degree of complexity increases because of the non-transparent presentation of the multi-model links and the interdependency within and between the construction elements. Previous studies show that human beings have difficulties with solving complex problems that come with mistakes and that eventually [7, 8, 9]. Therefore, information about the interdependency of the construction elements caused by the multi-model links has to be given. The highest priority should be given to the development of a user friendly information system which represents multi-model links.

4 Summary

The dynamics of today's business requires comprehensive, optimized processes that can be reliably performed only through the use of standards. The template methodology described in this paper is an example for process standardization extending the usage of CAD systems. Template technology provides all relevant process information directly from the CAD system. Each design stage can be performed by a template extension. The challenge for a suitable template concept is achieving balance between standardization and flexibility, as well as incorporating the ability to store and retrieve all information in a PDM system. Another significant factor is the acceptances of the user who has to realize the concept's succeed. Only a comprehensive approach to the development process, template methodology, and human behavior can implement this new technology successfully.

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Cross Disciplinary Methods for Accelerated Product Delivery

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Abstract
Consumer requirements for product convenience, functionality and quality have lead to an explosion of diversity and complexity of market offerings. Successful enterprises must use sophisticated and highly optimized engineering and manufacturing techniques to stay competitive. These same market demands drive products to market with decreased time available between introductions of new product models. These rapid innovation cycles must be executed with lean processes that are continuously improved and optimized yielding reduced costs.

Keywords
Knowledge Based Engineering, Product Development Process, Process Analysis, Process Optimisation

To help enterprises cope with these pressures, IT vendors are delivering software solutions that support more efficient engineering and manufacturing business processes. This has often been accomplished by developing tools that mimic physical processes, extending these software tools' functionality, improving their performance and expanding their scalability to meet rising enterprises' needs. However, the weight of global competitive pressures is forcing enterprises to make fundamental changes to underlying engineering processes. Today's design, engineering and manufacturing processes must be distributed, multidisciplinary and highly automated.

Supply chains continue to lengthen globally. Organizations must have ways to utilize insight from experts wherever they are in the world and whenever they are available to contribute. This global network of innovators must have reliable collaboration tools to supply them accurate information, to evaluate alternatives and to communicate their decisions.

The rapid innovation cycles demand reduced decision time. Practitioners from all disciplines must coordinate their decisions early and concurrently. Considerations from requirements, aesthetics, engineering as well as manufacturing must be balanced and reconciled as early and accurately as possible. Domain specific intelligence incorporated into the design digital product development environment is now routinely employed to augment engineering judgments. New tools are becoming available that can extend the automation to a distributed and scalable network of innovation.

IT systems, which are intended to support the digital product development, currently provide capabilities that let their users benefit from methods like parametric design, standard part re-use, digital mock-up and product structure editing.

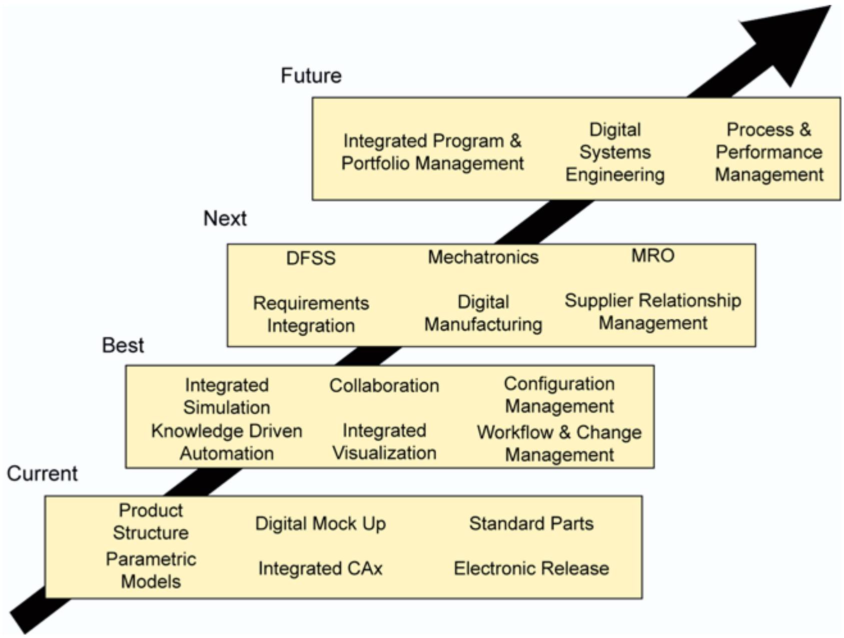

Fig. 1: Roadmap of Digital Product Development support

By leveraging knowledge-based automation techniques, push-button functionalities can be established in mechanical engineering tasks for generating variations of engineering solutions. Requirements can drive design parameters and initiate virtual validation procedures. Integrating business processes via common information backbones can eliminate wasted efforts in information allocation and re-use. Harmonizing the design intent with its consequences in the subsequent life cycle phases like manufacturing, assembly, maintenance and disassembly will eliminate complete loops of iterations resulting in lower engineering change costs. Methods like Design for Manufacturing, Design for Assembly and Design for Maintenance are being supported by today's state-of-the-art systems providing the incorporation of technology relevant information into the design environment.

Time spent iterating product engineering results until the released design is reached, can be shortened by corporate-wide integrated visualization techniques based on 3D representations of products. By "actively" combining packaging mock-up functionality with the design supply chain these 3D representations can be utilized to support engineering review processes during multiple phases of the product development process. However, the shape (form and fit) of a product represents only a portion of its many properties. A complete model of a product goes beyond its shape to include functional behavior, NVH and dynamic behavior under operating conditions. Performance and fidelity of the simulation tools for these models are critical.

A complete product model is far more complex than a traditional packaging mock-up. Today's increased dependence on mechatronic components drives electrical specifications, software functionality and their various configurations to the same level as shape and other physical properties. To cover this broad range of information, IT systems typically need to combine cross disciplinary functions to satisfy engineering decision making requirements.

The highest possible efficiency increase in the design and manufacturing phases of the production process, however, can be achieved by an end-to-end vertical integration between all the stages of the production ranging from virtual product development, down to the physical shop floor operations. Such degree of integration will introduce new possibilities of simultaneous product development, manufacturing planning and the design of the shop floor automation systems. Users of these combined technologies will achieve the highest quality, adaptability and fastest production processes.

Configuration management becomes important because of the diversity of product configurations resulting from different markets on the globe and various target user groups like consumer goods, automotive or defense. To support team work and to achieve combined usage of various applications in an engineering environment, collaboration strategies for IT systems need to be defined based on the target user scenarios. All functions and business relevant information of a globally distributed production enterprise need to be available at any location, at any time, concurrently. This is achieved by a Cross Disciplinary collaboration of IT systems in a network of customers and their suppliers.

Such networked engineering environments practice methods of co-design in multi-system environments. The simultaneous availability of manufacturing related rules and information during the design phases and the incorporation of these into the product and process models provide the necessary associativity between the product design and manufacturing processes as well as facilities. Since in conventional processes most of the critical make/buy decisions need to be made in the early stages of product development, the available cost data is usually imprecise. Practicing design for manufacturability with reusability considerations on processes and plants can minimize the duration of tasks prior to start of production and improve the precision of cost estimations for the production of developed goods.

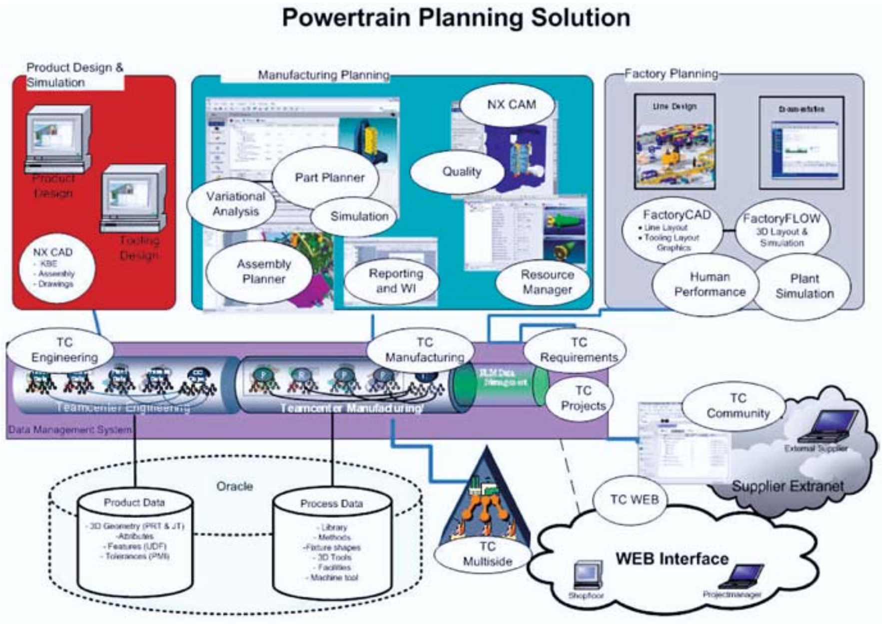

Fig. 2: Cross Disciplinary collaboration in an integrated Product Development and Manufacturing Environment

Given the economical challenges the industries face today, global outsourcing becomes a part of any production, introducing additional aspects of supplier integration. Issues of compliancy, IP-Protection needs, and fast delivery requirements need to be considered to streamline this major process. Multi-site capabilities of product, process, plant and resource information management is required with higher emphasis in these customer-supplier and supplier-supplier collaboration scenarios. Not only the management functionalities need to consider IP-protection issues in these scenarios but also multi-system architectures need to introduce methods of controlled information reduction for the exchanged models.

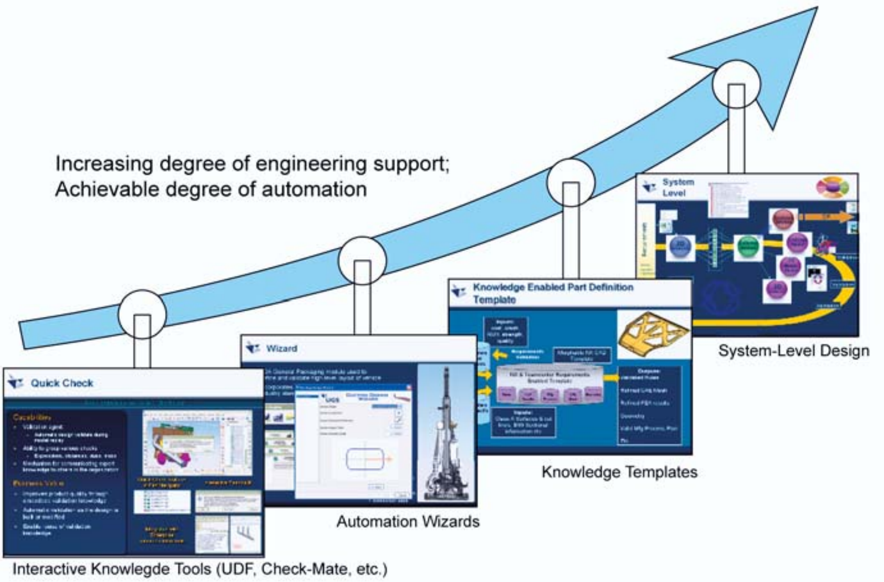

Fig. 3: Knowledge Driven Automation Strategy

The comprehension of the business processes in the target industries help the IT product and service providers to create process dedicated software solutions. The process awareness while designing IT tools opens the possibilities for knowledge driven automation strategies. The wide range of achievable automation and the degree of engineering support is provided by the diverse capabilities implemented for the specialized applications. The capabilities may range from user defined functions up to the utilization of wizards and knowledge templates, assistant software for product development. Thus a significant amount of room and time remains to introduce innovation in the processes. The path to creating innovation leads to cooperation between its creators, providers and users. Academic research, a responsive IT development team, as well as well defined and maintained business processes are therefore prerequisites for new successful practices.

Advances in PLM Methodologies Driving Needs for New Competencies

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Abstract
The daily practices in engineer's professions are a function of new work methodologies implemented by industrial companies as increments in their way to manage the lifecycle of their products. Such methodology innovations often find their first full scale implementation in business environments, as opposed to academic institutions. It becomes then a challenge for educational designers to develop the learning content that provides engineering students with the knowledge and skills required to operate, drive and evolve new practices in product creation. For technology providers, who contribute to the concurrent invention of new methods and new enabling tools, there are several ways to contribute to accelerate the transfer of their generic aspects from industry to education environment.

Keywords
Engineering education, Product Development Process, Process Innovation, Best Practices, global engineer, design in context, digital manufacturing

1 Introduction

Vendors of technologies that enhance the management of product lifecycle ("PLM") traditionally focus on improving various engineering methods and processes for industrial companies. Beyond this natural destination of their innovation effort, their potential contribution in helping educational institutions to increase their responsiveness in producing appropriate competencies is often underexploited.

This paper examines a selection of engineering activities that underwent significant transformations during the last recent years: (1) the accelerated use of composite technologies in large aircrafts, (2) generative design practices, (3) collective innovation practices, (4) multi-cultural engineering collaboration and (5) overcoming the cultural divide between product and production engineering.

2 The Accelerated Use of Composite Technologies in Large Aircrafts

With its 787 ‘Dreamliner” model, the Boeing company significantly accelerated the use of composite material in a large aircraft. This evolution is clearly driven by a competitive objective of reducing cost of ownership through reduced weight. Very large portions of the aircraft are impacted: all the primary structure, including the fuselage, wing box, and empennage boxes, are carbon laminates (a composite). The wing control surfaces are also carbon laminates, instead of the more traditional carbon sandwich.

This sudden acceleration has driven a strong need to retrain a large workforce from metal work to composites engineering and manufacturing. [3] Many aspects of engineering required to design appropriate curricula, including the design of new types of shapes for structure parts, dynamic analysis of skins, design of new manufacturing processes and resources, such as autoclaves capable to contain complete sections of fuselages.

Among this population, were several thousands of engineers using digital product / process creation technology (CATIA / DELMIA) and a shared collaborative infrastructure (ENOVIA). The competency transformation led by the manufacturer with the help of involved vendors had to target at the same time the employed workforce and students in academic education institutions. A vast training program was deployed for Boeing’s employees and their program partners. This program also reached initial education curricula in numerous higher education institutions within an extended ecosystem interested in aerospace education.

The revision of existing aerospace engineering curricula has taken several paths including some exemplary active learning [4] based projects as described by Leonhardt-Western Washington University and O’Charoen-Boeing Commercial Aircraft Group.

3 Generative Design Practices

3.1 The Extended Definition is at Work

A first level of understanding generative design describes the practice of computer aided derivation of similar parts from a generic instance through simple mechanisms such as parametric dimensional variations. This version of generative design, while interesting for accelerating routine or standard design, does not have significant organisational impact within product development organizations.

The extended understanding of the practice has been formulated in the late 80'ies by the Chrysler Company under the term "morphing". Morphing, in the context of vehicle design, was specifically targeting the body-in-white definition process that relates to internal body structures which are determined by a broad set of technological – sometimes empirical – knowledge rules, on one hand, and by the external (visible) body shape, on the other hand. The capability to change the outer shape definition as late as possible in the development schedule is a factor of competitiveness since it enables car makers to adjust the appearance of their product to a more accurate forecast of the market's aesthetic expectations. However, late changes in the outer shape of a car are only possible if all downstream processes can adjust quickly. Among these processes, body-in white design is one of the most costly. Therefore, the capability to automate the production of updated computer models of body-in-white structures that are technologically valid becomes a key competitive advantage. This level of generative design is already implemented in a large scale by some automotive companies. It implies deep transformation forces towards more specialization between two classes of professionals:

- "Build Time" engineers, focusing their work on innovation, new ways to assemble body frames, new materials, etc... Their task is to provide validated generic models of body in white structures. These models become the generative material for the other type of professionals:
- "Implementation" engineers -or "designers"- who focus on the design of the car currently being developed. Their task is to reuse generative definitions and to instantiate them as fast as possible within the contest of the latest version of the outer body shape.

Not all organization may want to establish this dual specialization scheme. Smaller companies may choose to prevent specialization of engineering work. However some large car makers have clearly reinforced the polarization of competencies. (Fig. 1)

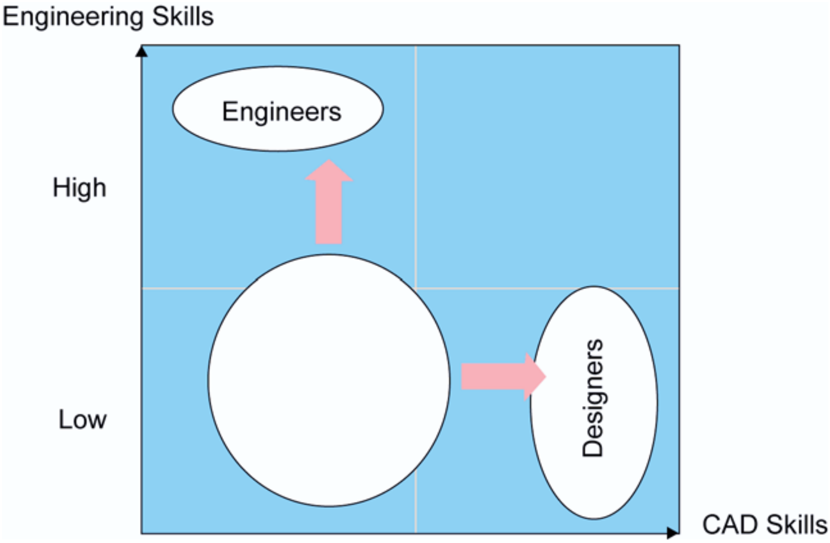

Fig. 1: Generative design practices, when deployed on a larger scale, determine two specializations of engineering profiles.

3.2 Teaching "Morphing" or Morphing Teaching?

A first challenge that generative practices pose to educational institutions is about reflecting the specialization of profiles. One could think that the "designer" profile is prepared in college studies while the task of creating generative knowledge is more relevant at Master level. In any case there is a need for future "build-time" engineers to understand the role of "designer" profiles and vice-versa.

The development of specific competencies such as knowledge-based modelling of generative objects requires students to be put in the situation of creating practical examples of realistic generative products. In many cases, it is therefore necessary to design substantial curricula evolutions. To help educators doing so, Dassault Systemes, as a vendor involved in the first industrial deployments of "morphing", provides academic users with start up teaching material to be inserted in their personal courseware.

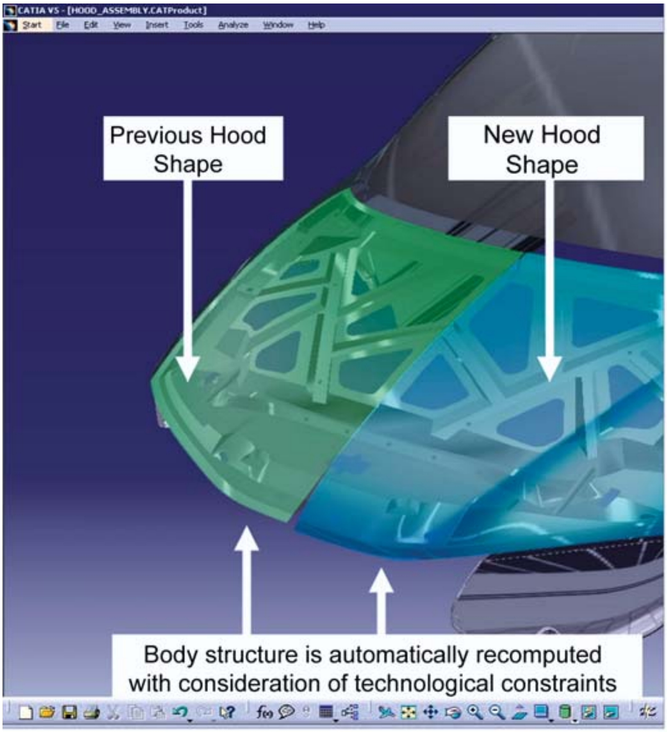

Fig. 2: An example of morphing: the complex geometry of the hood structure is determined by it's outer shape. When it changes, the new shape of the structure is recomputed with respect to knowledge rules that are active within the model. These rules guarantee that the geometry change of the structure still complies with the company's knowledge

3.3 Collective Innovation Practices

As soon as multiple players are simultaneously involved in developing a new product, typical project management issues arise, such as:

- Ensuring the consistency of the complete product while not over constraining individual's creativity,
- Creating the conditions for uniform progress of all involved engineers,
- Remove the cost of waiting for other team member's input?

A modern response to these issues was first implemented by the Bombardier aerospace company and was deployed for the first time in the automotive industry by BMW as part of their "Digital Car" project. This response was articulated around "design in context", a collective innovation practice that builds on the premises that all participants within a project publish their results daily. The technological enablers of this process include advanced publishing capabilities, complex query ("by zone") functions, as well as appropriate tools to perform local assembly consistency diagnosis.

3.4 Teaching the Social Aspect

The working dynamics created by design in context are various but the most spectacular is that it establishes "pull the input" forces (as opposed to "wait for output"), since it provides collective visibility on what are the most needed results a any time.

The social implications of establishing this effect are significant:

- Engineers must accept to publish preliminary ideas
- Engineers must accept to build on preliminary results from others.

To accelerate teaching of not only the technology but also the managerial aspects of such kind of practices, Dassault Systemes provides partnering institutions with specialized Master level conferences resulting from actual implementation projects.

4 Multi-cultural Engineering Collaboration

Globalization of product related businesses drive the need for a new kind of engineer's profile that reflects among other skills the competency of producing results in a collaborative effort that involves engineers, from one or several other countries or cultures. This has been recently articulated in a report [1] commissioned by the Continental company to several world class Universities. The first among four conclusions developed by the report is that "Global competence needs to become a key qualification for engineering graduates". This constitutes a general challenge for any institution willing to produce "global engineers".

During the 2006 Global Colloquium on Engineering Education of the American Society of Engineering Education, around 60 students were invited in Rio de Janeiro from various places to participate in the first Engineering Students forum associated to the colloquium. Most of the invited students had experiences of international relationships in an engineering context. Dassault Systemes conducted a survey of their perception of efficient education practices when developing competencies of a "global engineer". In one of the questions, students were asked to rank education practices from the most to the least efficient in developing skills for international collaboration in engineering. The results (fig. 3) reflected two trends:

- Students considered that the most efficient practices are those that immerse them into a foreign context,
- Student considered as efficient those practices that produce results within joint project.

Dassault Systemes has encouraged several international collaborative experiences that are characterized by the observation that was underlined in the survey: to create realistic conditions for concurrently learning the aptitudes and the attitudes of the global engineer, curricula that lead to joint realizations are highly efficient.

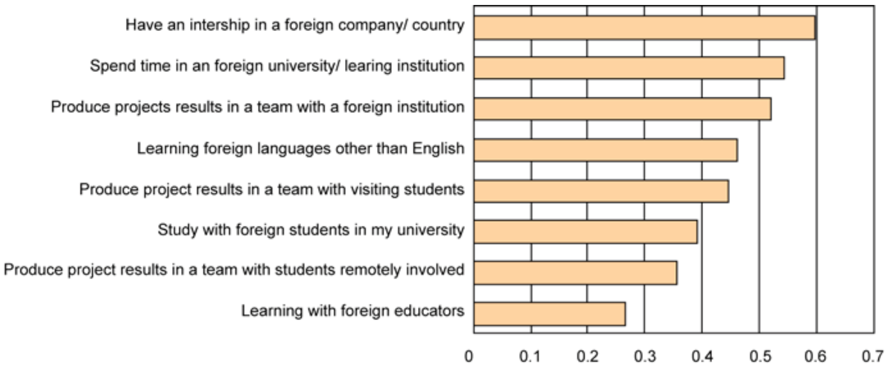

Fig. 3: The Rio survey was capturing a perception by which students could rank several education practices. Practices could score from 0 (least efficient) to 1 (most efficient)

4.1 An Indo-French Example or Result-oriented Project

An example of interesting multi-cultural experience involved an Indian and a French institution (college type). The actual project was to design and manufacture a mobile soft drinks vending machine. The students not only executed the project in the context of distant teams and shared content, they could also analyse their interaction within the network (Fig. 4) of interdependent tasks. The resulting learning experience is now inspiring further developments.

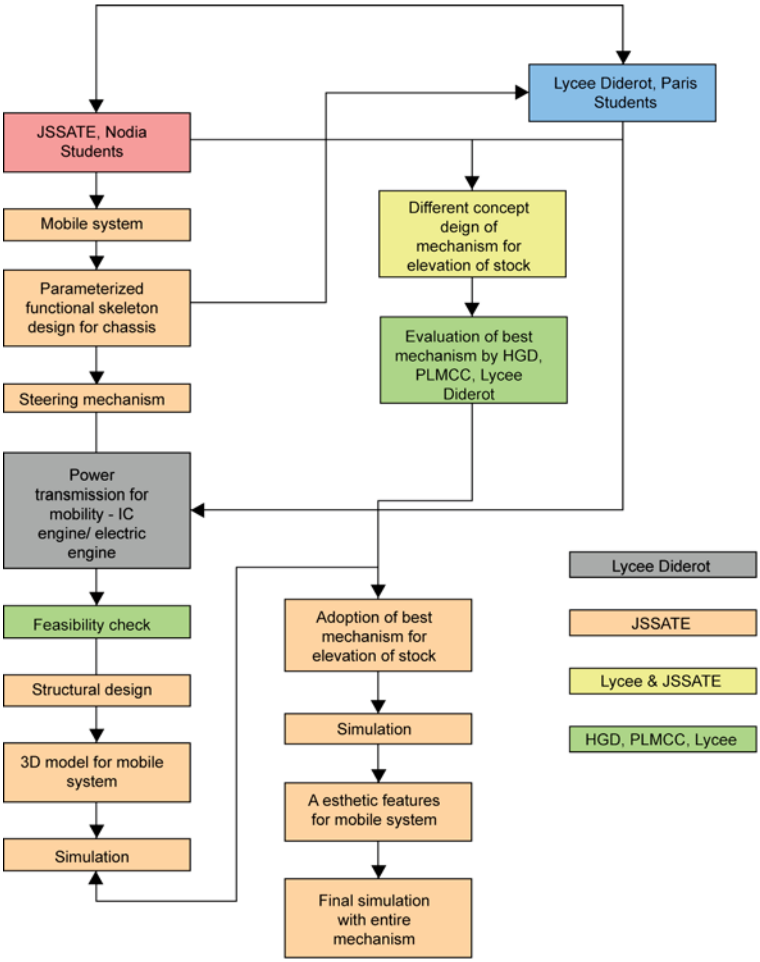

Fig. 4: Indian and French students established after the fact the actual flow of action across work packages and countries that led to the completion of the mobile soft drink vending machine

5 The Cultural Divide between Product and Production Engineering

Manufacturing industries invest considerable amount of investments and organizational efforts to establish more concurrency between product engineering and manufacturing engineering. Digital Manufacturing techniques are enabling and structuring these efforts [2].

However the cultural distance that tradition has established between these disciplines persists. Education can efficiently participate in establishing the role of engineers in a collaborative mode, while teaching the practice of concurrent definition of products and processes. Digital manufacturing provides a very appropriate framework [5] for developing this competency. The underlying principle in building digital manufacturing curricula is that it enables to import the model of the factory and its operations in the classroom. This provides product engineers with the factory point of view on the product development process and helps them conceptualize and practice concurrent product/process and resources design in teams that *simulate the different involved disciplines*.

6 Summary

Manufacturing industries provide the full scale test bench for new methodologies and processes in Product Lifecycle Management. Actual engineering practices become professional characteristics in this industrial context, even if their initial articulation originates in academic research. It becomes a frequently observed challenge for education to turn new practices into consistent elements of curricula. Technology vendors can invest in helping the transfer of this knowledge by means of specialized courseware, specialized educator's education, involvement in lectures, support of educational experiments, etc...

This paper explores *selected* examples that actually linked new industrial methods with educational practices. It outlines several key aspects of that can be implemented successfully in engineering curricula and it provides suggestions about possible contributions of vendors of enabling PLM technology to accelerate curricula construction and to help enhance educational responsiveness to industry changes.

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A Systematic Approach to Product Development Best Practises

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Product development today is defined by the complexity in products, processes, and a globally distributed value chain.

Product modularization and single sourcing, efficient program and project management, global collaboration and the ability to integrate mechanical, electrical and software design disciplines into one streamlined process are key success factors.

An open information backbone for integral product development is the key prerequisite for successful product development – a PLM system that will enable corporations to:

- Manage the complete product structure and product information from various sources in one integral system, leading to an optimized, lean product development process
- Enable true cross-discipline development that helps to increase product quality and reduce overall development costs.
- Efficiently manage programs, information, resources, and schedules through collaboration portals

1 An Open Information Backbone for Integral Product Development

The development processes for most of today's products - system design, detailed design, validation and configuration management – involve a complex network of disciplines, systems and individual applications from design, simulation and digital mock-up to documentation and downstream business systems for sourcing, manufacturing, and service. Isolated systems and processes today make it difficult to obtain complete and transparent view of the entire product as it is being developed.

Providing a single, integrated product development platform, enables the efficient management of design data from various sources as well as associated information like documentation, illustrations and engineering calculations. Integrating information from various sources and disciplines creates total product confidence from the first design iterations to SOP.

2 Systems Design and Mechatronics

Product development, in the past dominated by mechanical engineering principles, is undergoing massive changes and Electronics and Software engineering play a more significant role in product development.

The challenge in the system design, change management, validation, and quality management processes lies in the fact that the individual development disciplines often collaborate insufficiently, resulting in required changes being discovered late in the development process, causing unforeseen cost and quality problems.

This allows corporations to plan for quality through cross-discipline product development and avoid late, expensive changes.

3 Collaboration

Product development today requires close collaboration with design partners, suppliers, and manufacturing.

Collaboration needs to take place in a secure environment protecting intellectual property, and must ensure that up-to-date product information is being used.

PTC provides a collaboration portal solution with role- and task-based access, enabling secure and efficient collaboration within the extended enterprise and across the supply chain.

4 Solution Capabilities

PTC today combines four core product families – MCAD, PLM, Technical Documentation and Illustrations, and Engineering Calculations - into one integral and open system differentiated by a broad footprint of capabilities, clean architecture, that is easy to use, scalable to meet the needs of a global supply chain, supports incremental adoption to deliver value quickly while reducing risk and total cost of ownership.

SPALTEN Matrix – Product Development Process on the Basis of Systems Engineering and Systematic Problem Solving

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Abstract
The SPALTEN Matrix is a holistic product development process approach, which combines system engineering, the phases of the product development process and a systematic problem solving to one successful approach to handle complex product development processes. The SPALTEN-Matrix is the process backbone and cooperation, coordination and information platform for the product development process. This approach provides a long term planning and situation oriented problem solving during the product development process.

1 Introduction

Many different product lifecycle processes have been developed during the last years and the specialization of development processes is getting more and more common. Examples for this trend are the specialization of the development processes of mechatronics and micro technology [1]. The stages of these product development processes can be compared but they differ substantially with regard to the interactions and order of the single process steps. E.g. in the case of micro technology, the manufacturing method influences already considerably the ideas and the conceptual stage, because the production restrictions have to be known at this point of the development [11]. These different technologies show that there exists no general product development process. Product development processes depend always based on situation- and environment-related planning and modification. These circumstances create a demand for a reference model for the product development from which it is possible to derive specific development processes. The aim is to establish a reference model that indicates and supports optimally its adaptation to product-specific features. This paper presents a model for product development processes that is based on a continuous systems engineering approach in combination with the stage model and a team-oriented problem solving cycle.

2 Product Development Processes

Product development and innovation processes are being researched by several different domains. Thus, different domains propagate and develop continuously new approaches. The most active actuators in the field of innovation- and development processes are the management and engineering sciences. Many of these approaches have a special focus on their own domain. This fact can be clearly seen in the case of the design-methodical approaches. They start the development process with the clarification of the development task and the creation of the requirement specification. Many business management approaches, in contrast, end with the requirement definition. Especially Cooper was a decisive influence in the 90s in the change from the design-oriented development processes to business management-oriented product development processes [6]. From these two domains result two dimensions of a development process: design methodology and business management. The task of a development process is to manage the development project and to support the developers themselves during the development process. The success of a development process depends on the consistency and continuity of the single dimensions and stages. Prasad seizes this suggestion and divides the elements of a development process in different hierarchy levels – organization, product, and process [15]. These dimensions of the product development process are characterized by the stage-oriented protection, the objectives, and the navigation, by the development process itself. This view was founded by Blass, Franke, and Lindemann in the VDI-guideline 2221, in which the stages of the development process are connected to a problem solving process [20]. It is often used as the basis for the design of development processes. Gierhardt divides the model into process level, organization level, and product level, with a target and a knowledge level [10]. In brief, the development process can be divided into systems, methods, and processes, which again link targets, information / knowledge, and activities.

2.1 Systems Engineering and Product Development

The basics of the systems engineering-oriented perspective were founded by Patzak [14] and Daenzer/ Huber [7]. Ehrlenspiel transferred the systems engineering approach to product development processes [8]. Describing a product, he refers to it as system of objectives, which is the sum of the objectives (requirements) and their relations. In the system of objectives, the requirements are hierarchically structured according to their importance and the chronology of the sub-requirements. The result is the requirement list and system specification, they are the basis of the evaluation of each developing object system and of the development- or operation process. The market or the consumer that the product is manufactured for has of course also a large influence on the system of objectives [8] Ehrlenspiel defined these approaches, but he did not apply them consistently in practice. In the work of Negele, the systems engineering approach for the description of development processes was revived [12]. Negele developed the ZOPH-model (German: Ziel-, Objekt-, Prozess- und Handlungssystem, target-, object-, process-, and operation system) for the product development. He divided the operation system defined by Ehrlenspiel into process- and operation systems. Steinmaier reduces this approach and combines operation system and process system again to one operation system [18].

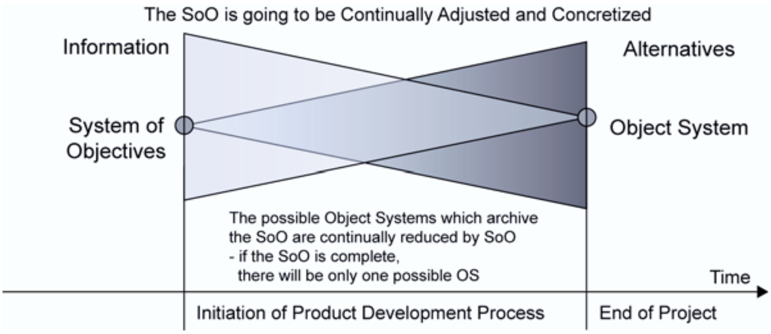

Fig. 1: System of objectives, object system in the product development process

In the systems engineering approaches, similar as in the problem solving processes, the system of objectives can be defined as target state and the object system as actual state. With these systems engineering approaches, the product development can be described as the transfer from a system of objectives, being still vague at the beginning of the product development, to a concrete object system. I.e., the core activity of the product development is the continuous expansion and specification of a system of objectives, the creation of an efficient operation system and therefore the successful realization into an object system – the product (Fig. 1).

Die VDI-guideline describes the process for the development and design of technical systems model in seven steps [20]. The process model of Pahl and Beitz reduces the process to four main stages [13]. Both process models start with the clarification of the development task; this step leads to the requirements, i.e. specifications that accompany the development process. These process models are sub steps of the product creation process and separate the development and design from the remaining product life cycle. In the nineties, it was recognized that the process steps in the development process are not sequential, but highly parallelized and with interlinking. Ehrlenspiel [8] resumes this approach and integrates the personal, informational, and organizational aspects into the product development process; he establishes the “integrated product development”. The product life cycle is described by means of systems engineering. The influences of all systems on the complete system, e.g. customer, product, production, human resources, methods, etc., are examined holistically.

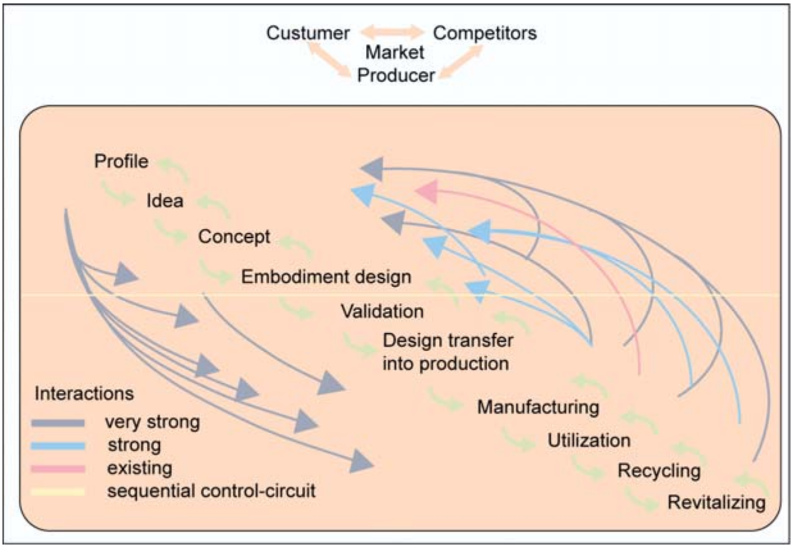

Fig. 2: Stages of the product lifecycle [3]

The process model of Albers (Fig. 2) displays the single stages of the life cycle and emphasizes the overlapping and parallelization of the stages and thereby it describes the interaction of the single stages [3]. The market and its three players (customer, competitor, and the producer himself) is the starting point. Albers incorporates the entire life cycle.

Cooper describes the change of the development processes in three generations. In the first generation, the relation of the single stages is primarily a supplier-to-costumer relation. The further development of the processes leads to the stage-gate approach of Cooper's second generation, in which the single stages are separated by gates. The approach of the third generation is Cooper's request to replace the gates of the single stages by fuzzy gates. The difficulty with a process where the stage limits are eliminated is the coordination of the complex interaction of the stages and the establishment of a clearly defined lead process [6].

2.2 Problem Solving Processes

Basically, a problem can be described as delta between the target state and the actual state. Two kinds of problems can be distinguished: the emergency and the planning situation. In the emergency situation, the actual state declines and the target state remains the same, whereas in the case of the planning situation, the target state as objective is actively changed so that the actual state needs to be adjusted [4] (Fig. 3).

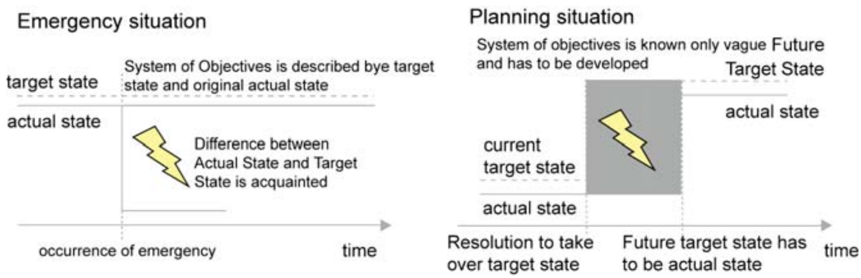

Fig. 3: Problem situations

The most elemental problem solving process is the TOTE-schema (Test-Operate-Test-Exit). The aim of this schema is to achieve the target state or objective by changes or operations of the given actual state. This schema can be considered as closed loop [17]. This closed loop is repeated in iterative steps, until the desired state is achieved. For this purpose, a variety of problem solving cycles and models were developed. Here, the problem solving process according to the VDI-guideline 2221 has to be mentioned, which is substantially adapted to the system technology or systems engineering. This process represents the stage-oriented procedure of the product development, i.e. a macro process. Most problem solving models have not been established as standard process. In practice, stringent problem solving methods for emergency situations are of a greater importance, here, the VDA 8D-report is well-tried [19]. It supports e.g. SAP systems as standard process for customer complaints [16].

The developed SPALTEN-process (German: spalten = to split, to decompose) is a holistic problem solving process. It describes a universal procedure for the solution of problems with different boundary conditions and complexity degrees. With its help, an effort and time minimization as well as a solution optimization and safety maximization for the problem solving can be achieved. The areas of application of the SPALTEN-method are the future-oriented as well as the spontaneously occurring problems. This problem-adjusted procedure enables an optimized benefit-/effort relation. Here, the procedure is not to be applied dogmatically but pragmatically depending on the boundary conditions. (The seven steps of SPALTEN: 1. situation analysis, 2. problem containment, 3. finding alternative solutions, 4. selection of solutions, 5. analyzing the consequences, 6. deciding & implementing, 7.finally recapitulation & learning) [2] (Fig. 4).

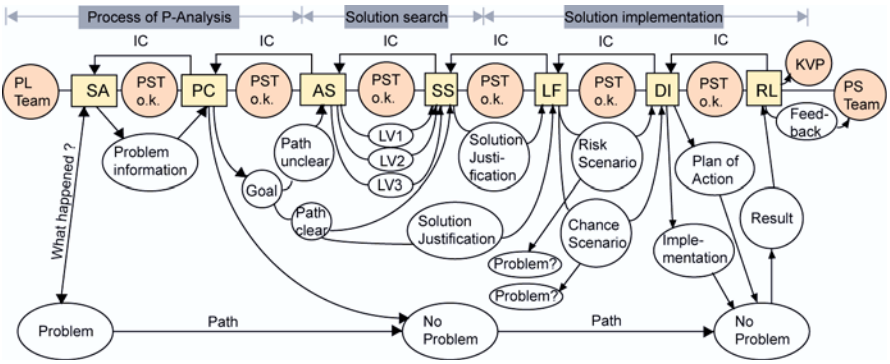

Fig. 4: SPALTEN-process

2.3 A Reference Model for Development Processes

In general, product development can be understood as problem solving. In the product development process, the problem solving has two dimensions: the life cycle from the profile phase to recycling phase, and the problem solving of the single stages from the situation analysis to the recapitulation and learning. Gerst defines theses two dimension of problem solving in the product life cycle as the macro-logic and micro-logic of the product development [9]. Based on these different approaches, a reference model for the product development was created that displays the different dimensions and supports the different views and approaches.

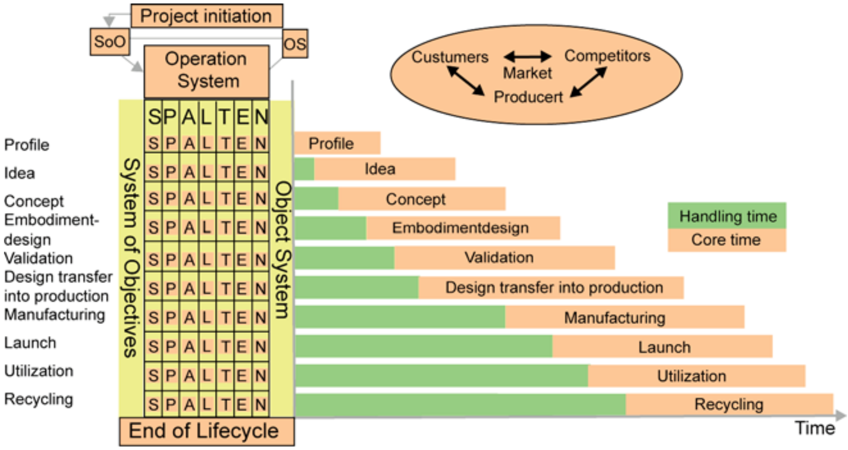

Fig. 5: The SPALTEN-MATRIX reference model

The core element of this model is the holistic referencing to the system of objectives and the fractal problem solving process SPALTEN during the entire product development process. The base of the process is the system of objectives that specifies the objectives that describe the future, anticipated or planned target state (Fig. 5). The system of objectives describes all relevant objectives and their dependencies and boundary conditions that are relevant for the development of the right solution – from the current actual state to the future actual state; the solution itself is not included [12]. In the course of the product development process the system of objectives is constantly expanded and concretized. The correct, continuous and complete collection and adaptation of the objectives is the foundation of a successful product development and a decisive part of the development activity. From this system of objectives the socio-technical operation system is derived, it includes structured methods and processes, as well as the resources involved in the operations for the achievement of the objectives. The operation system creates the system of objectives and the object system.

The result of the operation system is the object system, the implemented solution of the system of objectives. The object system is completed, when the planned target state corresponds with the actual state. Object systems are not only material systems, but also immaterial systems, e.g. in the case of software and services [8]. The object system comprehends the operation results developed for the problem solving or the achievement of the system of objectives, i.e. besides the result itself, also all intermediate results (e.g. drafts, prototypes) developed in the operation system [21]. The elements of the object system are subject or result of the operation system. The problem solving process SPALTEN is the fractal micro-logic of the operation system. All process steps are structured and documented according to the SPALTEN-process. The fractal nature of the SPALTEN-process means that the SPALTEN-process is repeatedly implemented in each problem situation of the process. It has been demonstrated that SPALTEN is effective and successful for the implementation and documentation of problems. Especially the standardized procedure enables the interchange ability. The process step is the basis for a standard language for the dealing with problem situations in different domains. The interactions of the single stages of the product development process are controlled objective oriented with SPALTEN, based on the system of objectives. If e.g. the problem containment of the idea stage identifies restrictions concerning the manufacturability, the situation analysis of the production planning is started, the results are replaced in all stages of the system of objectives and made available for all stages.

3 Conclusion

This reference model creates a problem-oriented process control during the entire life cycle. At the same time, all process steps can be development-methodologically supported. The continuous model enables a standard language on the micro and macro level in the product life cycle and standardizes stage- and domain overlapping views of the product development process. With this reference model Cooper's demand for a development process of the third generation is realized, stage changes and interactions are situation-specifically detected, implemented and protected by the problem solving process. With the documentation of the process model, the single steps of the SPALTEN-process cannot only be observed singularly in one stage, but also the entire life cycle. The reference model creates new possibilities in the methodical process support. Each step in the process, the cross point between micro- and macro cycle, can be provided with suitable auxiliary means accessible for the developers. The first studies demonstrated that the reference model offers many possibilities especially with its stringent division between system of objectives, object-, and operation system and the separation of the single steps of the problem solving.

4 Perspectives

Wikis as open content management systems in Intranet und Internet for information and knowledge platforms have reached a very high acceptance and penetration in only a short time. In a larger development project with 40 developers the IPEK used a Wiki as cooperation- and communication platform for a product development process and tested it with regard to its applicability. The potential of such Wikis is undisputable; many companies begin to build up expertise- and knowledge management systems based on Wikis. In the scope of the development project, the process support was very successful and the Wiki added substantially to the positive result of the project. The open structure of Wikis offers many advantages; however, it can also cause problems. When Wikis are used in product development processes, it is necessary to pre-define the structure, and here the reference model can be an ideal substructure. In further research projects, the reference model of the product development will be applied to an Internet-based Wiki. With this Wiki, the process navigation, -documentation, and project controlling will be carried out for the entire development.

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How to Measure the Success Potential and the Degree of Innovation of Technical Ideas and Products

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Abstract
The evaluation of innovative ideas and products with regard to their success potential – in terms of market penetration – and the degree of innovation is a special challenge for research and development departments as well as for management. Therefore a new evaluation method was developed to quantitatively determine these two characteristic values. The basis of the new method is Quality Function Deployment, which was modified and expanded to consider aspects of novelty and enhanced customer and manufacturer benefit. The evaluation of the method in five pilot projects shows that the calculated evaluation figures are very well suited for decision making in the product development process.

Keywords
Evaluation Method, Degree of Innovation, Innovation-management

1 Introduction

Innovative products are the key to success for all enterprises, especially in a competitive global market [3]. As far as economics is concerned, innovation signifies the introduction of an idea into the market or the conversion of scientific results and new ideas into a market economy-related or technical realisation [1]. In order to successfully develop innovative products, methods are necessary which are particularly related to the innovative parameters “novelty” and “successful commercialization”.

A review of the literature regarding development processes for new products indicates that there is still no quantitative appraisal and evaluation method which integrates the complex central factors “novelty” as well as “enhanced customer and manufacturer benefit” – and it is these factors which are the crucial final determinants of the success of a product.

In order to launch successful products, a detailed knowledge of customer requirements and their conversion into product requirements is necessary. The most exact possible fulfilment of customer requirements is an essential criterion for quality.

A new evaluation method should be able to identify the chances of market penetration (success potential) and the degree of innovation of technical product ideas and products. The objective of this new evaluation method is the determination of quantitative parameters to measure these two abstract items and to enable a comparison with other products (preceding models or competitive products). For the beginning, the method should focus on scientific-technical aspects.

Conventional methods, such as selection and evaluation methods, or methods for designing for quality, e. g. FMEA and QFD, are not sufficient to evaluate innovative ideas and products according to the objectives of the new method. Even if these evaluation methods of design engineering are modified accordingly, it is not possible to quantitatively determine the parameters of innovations, market penetration capability and degree of innovation.

2 The Key to the Solution

Updated definitions of genuine “(product) innovation” imply that a product not only has to be *new,* but also *successful* on the market [4]. A product can certainly be called “successful” if it offers a higher benefit than other products to both the customer and the manufacturer and if it is accepted on the market. The following definition can be derived from this analysis:

A product innovation is the successful realisation of a creative new idea or invention with an enhanced customer and manufacturer benefit.

According to this definition, the task of making innovation measurable raises the problem of how to quantitatively determine the degree of novelty and the enhanced customer and manufacturer benefit of an innovation (Fig. 1).

Since *customer benefit* can be equated with the best possible fulfilment of customer requirements, the new procedure must, as a first step, analyse customer requirements and their conversion into product requirements. To achieve this, the solution approach uses elements of the QFD method. Based on the first QFD phase, the evaluation method was enhanced by the following steps:

1. Product survey by means of the QFD method to obtain important parameters from the customer and product requirements for the evaluation algorithm.
2. Modification of the QFD matrix to record the importance of the novelty of the product.
3. Analysis and recording of influencing variables for each product requirement by modifying the QFD matrix.
4. Creation of an evaluation algorithm to determine the success potential and the degree of innovation.

These solution steps are the basis for the new evaluation method which is described in the following [5].

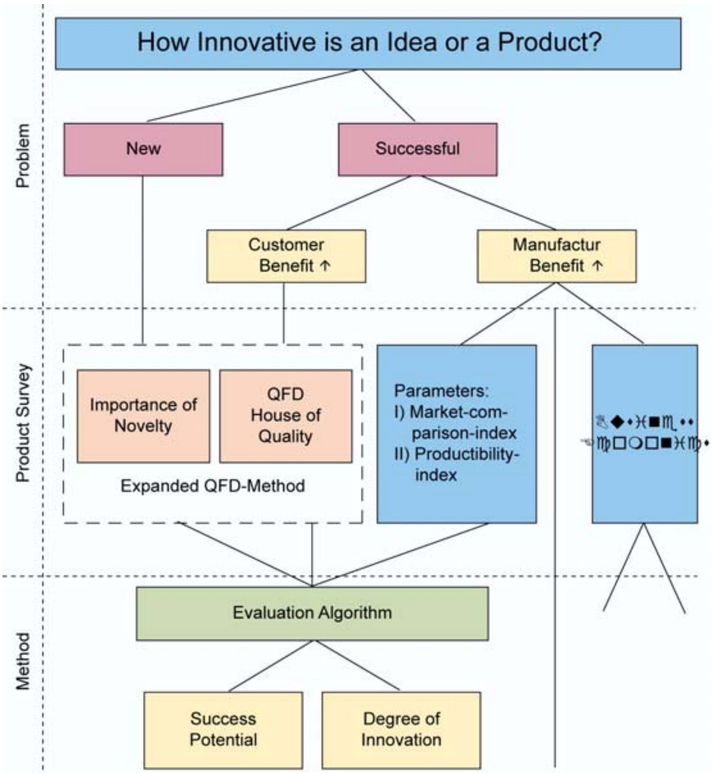

Fig. 1: Solution approach for the evaluation of innovative ideas and products

3 Evaluation Method

3.1 QFD Product Survey

The first phase of the QFD method is, in a modified form, the origin for the appraisal and evaluation method (see Fig. 2). In order to allow the quantitative rating of the central parameter of an innovation, the *novelty of the product*, the column “importance of novelty of the customer requirements” and the row “importance of novelty of the product requirements” must be integrated into the evaluation matrix.

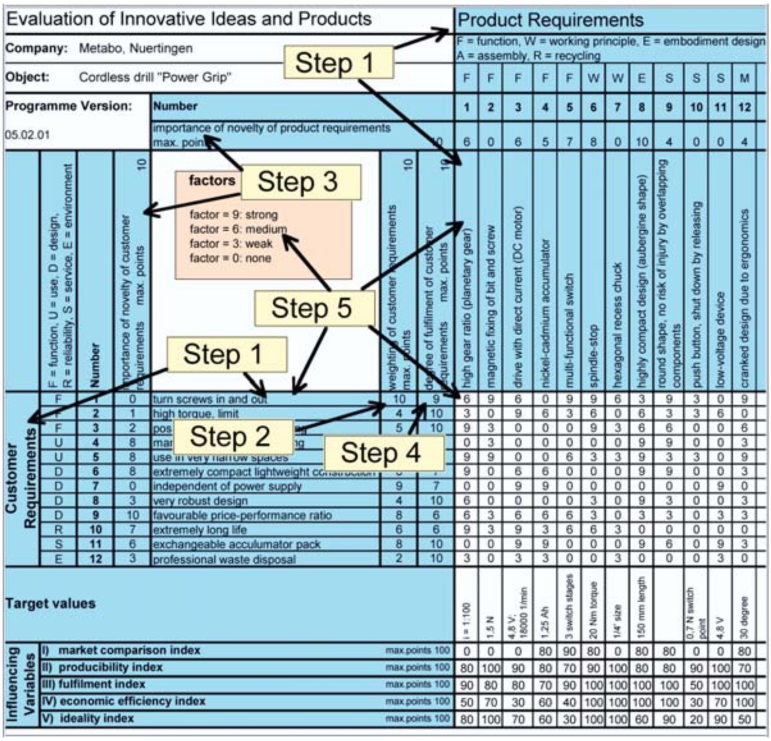

Fig. 2: Procedure to fill in the evaluation matrix

The procedure for drawing up the evaluation matrix is divided into the following steps:

1. The customer requirements are entered vertically, the product requirements are entered horizontally.

2. The customer requirements are weighted according to their importance.
3. Determination of the importance of novelty of the customer and product requirements by using a scale from 0 to 10 points. If, e. g. for the product requirement no. 1 in Figure 2 “high gear ratio”, the value 6 is entered for the importance of novelty, then the “share of novelty” in the product requirement is estimated to be 6/10 or 60 %.
4. Determination of the degree of fulfilment of the customer requirements by quantitative identification of the values in comparison to competitive products (bench marking).
5. Correlation between customer and product requirements.

The technical importance of a product feature according to the QFD method is the key variable for an evaluation because it includes the important aspects “customer orientation and technical feasibility”. The technical importance is determined according to the following steps (Fig. 3):

1. For all product requirements, the correlation factor is multiplied by the weighting factor of the customer requirements.
2. Addition of all these (mathematical) products within a product requirement. This is carried out for all product requirements.
3. In a further step, it is advisable to calibrate the calculated values by use of a scale from 0 to 100.

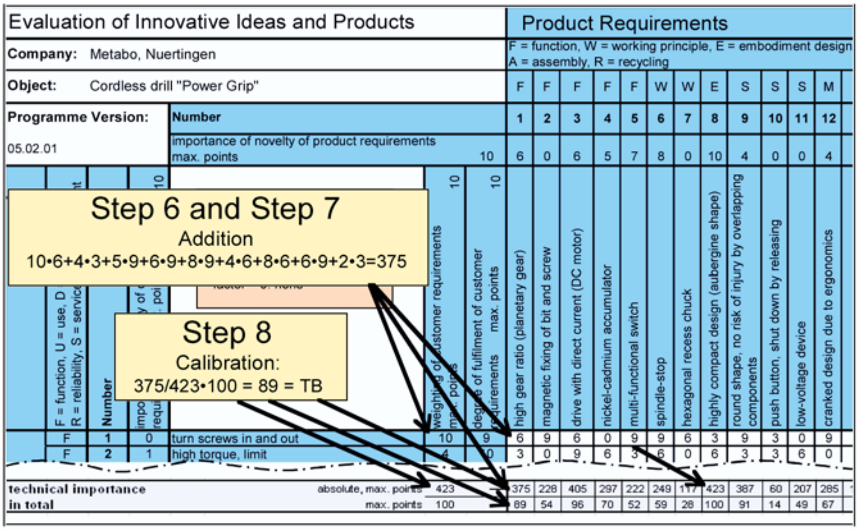

Fig. 3: Determination of technical importance

3.2 Influencing Variables on Product Success

The evaluation matrix is extended by the influencing variables on product success (Fig. 2). They are necessary for a comprehensive evaluation with regard to the *enhanced manufacturer benefit* of an innovation. The individual influencing variables range from 0 to 100. High values represent a positive effect on the product success.

Comments on the influencing variables on product success:

1. Market comparison index:
   The data to be entered must be assessed by comparing the objectives of the product under analysis with the objectives of the competitive products since realistic data can only be obtained by permanent long-term market observation. High values must be entered if the product has a high performance.
2. Producibility index:
   This assessment requires the knowledge of experts. A high value represents a low manufacturing risk. In general, the risk of failure depends on increasing manufacturing difficulties.
3. Fulfilment index:
   These values refer to the reliability and the probability of fulfilment of the product requirements.
4. Economic efficiency index:
   As far as the economic efficiency aspects are concerned, costs, complexity of manufacturing and assembly, investment costs, etc. must be moderate to ensure economic success.
5. Ideality index:
   This index includes the need for additional functions to achieve the objective. Therefore, a solution with a high "degree of ideality" is also a solution with low destructive side effects [2].

3.3 Calculation of the Success Potential and the Degree of Innovation

In order to determine the success potential and the degree of innovation, indicators must be identified by a mathematic link between the key variables from the QFD product assessment, the *technical importance* of the product requirements and the *influencing variables on product success*. These indicators should reflect the degree of fulfilment of the customer requirements and the feasibility of the product requirements including all prerequisites and risks.

Calculation of the Valuation Factors

The determination of individual indicators is based on mathematic links between the technical importance and the influencing variables I to V. The links are represented in five portfolios. For example, Figure 4 shows the portfolio of the influencing variable “producibility index”.

Modus operandi:

1. For each product requirement, the value of the influencing variable is plotted versus the technical importance in the respective portfolio. Example: The product requirement no. 1 has a relative technical importance of 89 and a producibility index of 80 (Fig. 4).
2. By means of mathematic averaging, an individual valuation factor ($E_{I,i}$ … $E_{V,i}$) is assigned to the numbers pairs. Therefore, in the above mentioned example, the individual valuation factor is

$$E_{II,i} = (89 + 80)/2 = 84{,}5.$$

3. A total valuation factor (E_I … E_V) is calculated by arithmetical averaging of all individual valuation factors of one portfolio.

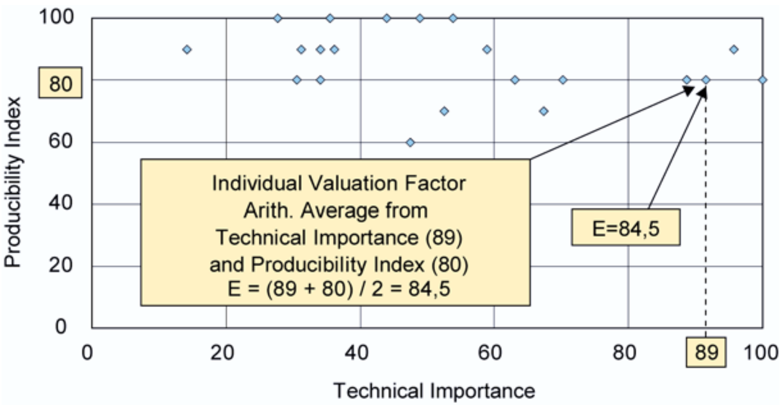

Fig. 4: Portfolio: Producibility index versus technical importance

Calculation of Success Potential

The average value is then calculated from the five valuation factors (E_I … E_V) resulting from the mathematical links of the technical importance and the influencing variables I to V. Because of the above-mentioned definition, an evaluated object with a high average value will most probably be successful on the market. This average value calculated from the influencing variables is identified as *success potential*. This specification now allows the definition of the term “success potential” on a mathematical basis:

The success potential of an innovative idea or product results from the average value of the valuation factors of the influencing variables on product success.

The success potential is calculated as follows:

Averaging of the (in some cases weighted) valuation factors of the influencing variables.

$$E_P = (p_I \cdot E_I + p_{II} \cdot E_{II} + \ldots + p_V \cdot E_V)/(p_I + p_{II} + \ldots + p_V) \quad (1)$$

E_P: Success potential
$p_I \ldots p_V$: Weighting factors
$E_I \ldots E_V$: Valuation factors of the influencing variables I to V

Calculation of the Maximum Value of the Success Potential

The calculation of the theoretically possible maximum value of the success potential is based on the maximum possible values of the individual influencing variables. The ratio of the calculated success potential to this maximum value characterises the capability of the test object, even if no comparable objects such as competitive products are available.

Calculation of the Degree of Innovation

The central parameter of an innovation is the importance of novelty of the product which has been determined by an estimated value of the importance of novelty for each customer and product requirement. By means of these numerical values it is now possible to determine the “share of novelty” in each technical importance of the product requirement (Fig. 5). The determined “shares of novelty” of the technical importance are the basis for continuing the calculation of the degree of innovation.

The following calculation is done in the same way as the calculation of the individual valuation factors. The technical importance – now only the shares of novelty – and the influencing variables I to V are also displayed in two-dimensional portfolios, the individual valuation factors are calculated and the influence valuation factors are determined out of this.

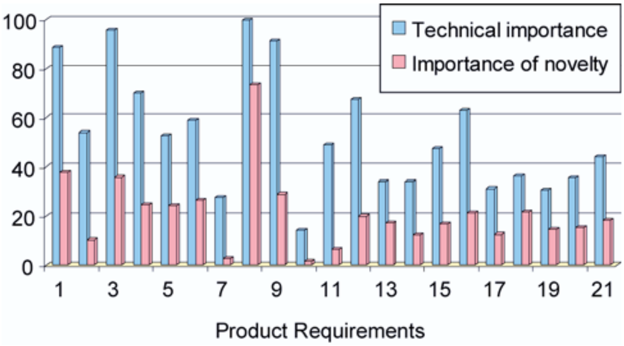

Fig. 5: Technical importance and importance of novelty of the product requirements

The degree of innovation of an innovative idea or a product is the share of novelty in the success potential.

The degree of innovation is then calculated as follows: Averaging of the (in some cases weighted) valuation factors of the influencing variables taking the novelty into account.

$$I_G = (q_I \cdot I_I + q_{II} \cdot I_{II} + \ldots + q_V \cdot I_V)/(q_I + q_{II} + \ldots + q_V) \quad (2)$$

I_G: Degree of innovation $q_I \ldots q_V$: Weighting factors
$I_I \ldots I_V$: Valuation factors of the influencing variables I to V *with novelty*

4 Validation of the Evaluation Method

The evaluation algorithm was tested and validated in pilot projects. On the one hand, this was carried out with products already on the market and, on the other hand, with innovative product ideas from the development and design phase. The pilot projects selected were typical projects of the consumer and the investment goods industry.

As an important result of the pilot project stage the following statements can be made. At the beginning of an evaluation, the object to be evaluated is often wrongly rated, i. e. the “importance” of success and innovation is overestimated. On a closer examination and analysis, many innovations are “simply” a new combination of already existing solutions. Only very seldom a “new, revolutionary idea or solution” is created. Therefore, mostly smaller numerical values, as expected from the previous qualitative and often general appraisals, result from this relatively accurate and sophisticated new evaluation method.

Tab. 1: Results of pilot projects

Project	Unit	Company	Success potential	Degree of innovation
A	Cordless drill ”Power Grip”	Metabo, Nürtingen	81,9 %	31,2 %
B	Snowblower	X	75,0 %	6,4 %
C	Modular multiphase low-cost electric drive	Y	81,0 %	38,3 %
D	Miniature translation stage	Festo, Esslingen	83,0 %	32,6 %
E	Independent steam	Braun, Kronberg	85,2 %	36,6 %

5 Conclusion

The following results arose from discussions with the companies involved about the applied procedures and the conclusions drawn from the evaluation data:

1. It is possible to evaluate individual segments of the innovation process of a product as well as technical subsystems during the development phase or products on the market.
2. The evaluation results are particularly qualified as a decision-making aid in product development.
3. Ideas and products mostly arise from a combination of conventional design elements and/or partial solutions for a new purpose. Real major novelties are seldom.
4. The evaluation method supports an overall entrepreneurial evaluation and gives important advice to the management with a view to improving an enterprise’s innovation capability.

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Towards a Generic Model of Smart Synthesis Tools

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Abstract
Software support for the solution generation phase of the design process did not yet have the same industrial acceptance as e.g. 3D modellers and finite element analysis. The "smart synthesis tools" research project aims to bridge part of this gap between academic research and industrial application. The goal is to deliver a generically applicable method and algorithms to develop dedicated synthesis tools for industrial design processes in a standardized manner. Research addresses problem structuring, mathematical techniques and handling of experience knowledge and qualitative relations. An efficient development methodology is expected to increase the accessibility and applicability of synthesis technology to both the research community and industrial parties.

Keywords
Computer Aided Design, Synthesis, Design Process Model

1 Introduction

In the last decades, industry is experiencing an increasing amount of pressure on time, cost and quality during the product creation and realization process [11]. The industrial need for a higher efficiency of the design process is addressed by both academics and commercial institutions.

This resulted in commercially available software support such as 3D modellers to improve communication and representation and advanced finite element analysis to increase performance prediction. Software support for the solution generation, or synthesis, phase of the design process did not yet have the same industrial acceptance, a sign that there exists a gap between academic research and industrial application.

The smart synthesis tools project uses existing academic synthesis techniques and focuses on four research topics that are of importance during the development process of new tools. Guidelines and algorithms are developed regarding the use of expert knowledge, smart structuring of complex problems and mathematical search techniques in large solution spaces. These topics focus on design processes with quantitative analysis methods. The project also researches design processes where these are not available: how to develop support software when only qualitative physics relations are available? Industrial prototypes are developed using the developed methodologies to deliver proof of principle.

First, the historical development of commercial CAD systems is briefly discussed. Although synthesis tools have not yet had a similar development, academic research yielded several advanced techniques and methodologies, a short overview of which is given. Secondly, the long term view in which the smart synthesis tools project is placed is presented, together with the four year strategy. The addressed research topics conclude the paper.

2 CAD Development

The historical development of computer aided drawing software is discussed briefly regarding the academic research milestones and their commercial effects.

The first sketch application saw the light of day at MIT in the early 60s, but it took about a decade for the first 3D wireframe sketch applications to appear, such as DUCT in 1974. The majority of the CAD development was done in the major automotive and aerospace firms, until the first generic kernels appeared in the beginning of the 80s: a CSG solid modelling kernel by UniGraphics and the Romulus b-rep solid modeller [www.cadazz.com/index.htm]. These kernels led the way for the first commercial CAD tools, e.g. AutoCAD and CATIA. These computer aided modelling systems enable clear representation and communication of designs and led to 70 different software systems with over 2 million users in the 1990s.

In this historical timeline, one can find a pattern of successful commercialization and acceptance in industry in CAD after academic research explored new possibilities and had evolved into a generic kernel.

Research in intelligent CAD systems started in the mid of the 1980s [5] and was noticeably intensive [1, 13] until the beginning of the 1990s. Certainly these research efforts formed the foundations of some crucial elements available in modern CAD systems; constraint-based problem solving and knowledge management.

A similar development pattern can be observed for the automation of analysis methods: as increasing pressure on the design process calls for less trial and error loops, a better prediction of product behaviour is required. Academic research established an analysis method that is generically applicable, finite element analysis (FEA), which led to a numerous variety of commercial packages, e.g., NASTRAN, ANSYS and COMSOL. Although they already cover such advanced problems as multi-physics, large deformations and dynamic simulation in many domains and levels of detail, possibilities are still being expanded further by (academic) research. FEA software is widely used in industry and academic research on this topic is flourishing. Just like 3D modelling, (academic) development in FEA led to generic software that supports a range of different industrial problems.

Commercial software for the solution generation activity is less available. Nevertheless, academic research into the field of synthesis is widespread: many techniques have been studied or are presently being researched and many prototype systems deliver proofs of principle.

One approach, typically found in the research direction of design theory and methodology, advances towards a generic synthesis 'kernel' to support a range of design problems. Although a reasonable amount of research effort has been paid, we are still not able to explain synthesis with a universal, generally applicable theory. Cagan et al. indicates that the act of formulating or initializing a synthesis process has not received much attention in literature, since most computational synthesis methods are developed to solve a particular design problem [2]. Some of those "simpler" models ever proposed are listed as follows.

- Simple solution generation and test
- Database lookup
- Search in a problem space
- Abduction, generative rules
- Case-based reasoning
- Grammars
- Computational models

Although each of these models can reasonably explain synthesis in a limited situation (for example, database lookup can be used for design in which design solutions are indexed and these indexes should cover the range of design requirements), none of them can explain design synthesis in a uniform manner. One possible reason is that no such model exists. Another possibility is that it does exist, but yet to be found. A good reason for the latter case is that it is hard to find due to the diversity of industry's design processes. For instance, Maimon and Braha [10] researched a formal model of the design process, focusing on the synthesis part. The main conclusion is that although high expressiveness is necessary to allow for the generation of a wide variety of designs, it might swamp the designer with alternatives. So, any increase in expressiveness must be accompanied by an increase in the designer's ability to control the complexity of the design space.

Maybe it is not so important whether or not such a universal model of synthesis exists, or even can ever be found. Confronting such a situation, one reasonable strategy could be to build a model that can flexibly combine known individual models and to try to explain as many different types of design as possible.

Another research direction is towards a generic development process for dedicated synthesis tools for individual design problems. This approach is being explored by the Smart Synthesis Tools project, funded by the Dutch Innovation Oriented Research Program 'Integrated Product Creation and Realization (IOP-IPCR)' of the Dutch Ministry of Economic Affairs.

This paper aims to provide a baseline for the Smart Synthesis Tools project. The vision in which this project is placed, the mission and strategy of the project is discussed in more detail in the following sections. Since the diversity of design processes in industry is vast, a selection is made regarding the type of the problems to address.

3 Smart Synthesis Project

The project has emerged from experiences in industry that the synthesis phase is under increasing pressure but poorly supported, together with a growing awareness of the gap between academic synthesis research and industrial application: academic achievements are applied in industry only sporadically [2]. The long term view in which this project is placed is addressed first, after the strategy and an outline of the relevant type of design processes is given. The approach on how to reach the project goals is translated into four research topics, presented afterwards.

3.1 Vision and Mission

The ideal role of software support during design is that the computer will take over the role of creating solutions, in an interactive fashion with the human designer. By doing so, synthesis is made as common as analysis and modelling. The role of the computer will change from machines that perform routine tasks on large amounts of data, to helpers in situations that require human intelligence. The emphasis shifts from data processing to knowledge manipulation for problem solving purposes. Examples are knowledge-based methods used for conceptual synthesis and design generation, such as a Knowledge-Based System for Conceptual Synthesis (KBCS) based on functional reasoning [6, 15] or the A-Design theory using collaborating agents and adaptive selection [3].

A gap is still present between academic research and industry regarding synthesis support. The project aims at closing part of this gap by researching the possibility of a generic development process for synthesis tools, thereby allowing efficient development of dedicated tools for industrial design processes. Having an efficient development plan ready to build synthesis tools for industry will increase the accessibility and applicability of synthesis technology to both the research community and industrial parties.

The mission for the smart synthesis project is to demonstrate the possibility of dedicated synthesis tools, which will create solutions in shorter time, and to increase the accessibility and applicability of synthesis technology.

3.2 Strategy

The strategy describes how to realize the mission goals in a four year period. The presented project aims to reach the mission statements by developing the following.

- Synthesis tool prototypes for several industrial cases
- Document generic knowledge:
  - Methodology of the development process
  - Toolkit (collection of common algorithms)

This project aims to develop several prototypes using and testing a common development approach. The tool itself should be able to generate solutions with higher quality in shorter time and allow for increasing (multi-disciplinary) complexity of products. The methodology to develop dedicated synthesis tools for industrial design processes is documented. It handles the process from entering a new company and exploring the design processes to the algorithm development itself. This translation process of an industrial design process into an automated synthesis tool has not received much attention by academic research. Generic pieces of software will be stored in a toolkit, enabling fast and efficient software development for future tools. The long term goal is to develop a generic (software) kernel that allows custom built synthesis support for many types of industrial design processes.

Several research topics are of strategic importance, discussed briefly. Each topic has an industrial case attached where proof of principle is to be delivered. The design process and knowledge on which the project will focus is addressed first.

3.3 Design Process

The project's focus is on design processes that are found in industrial and for which analysis is available. In Fig. 1, a representation of the development of knowledge from the principles of physics towards commercial applications is depicted.

On the qualitative side of the spectrum, the principles of physics are identified. Arrow A depicts researches to describe 'what' happens, leading to a qualitative description of phenomena and their relations. As research advances through arrow B, relations between system parameters, interactions and behaviour begin to emerge and are fixed by formulas and analysis methods. Arrow C translates the knowledge about these quantitative relations into an application, or product.

In a design process, arrow B can be seen as conceptual design, where solution principles are combined to produce a solution structure to deliver the required behaviour. Arrow C is the embodiment design phase, where parameter values are determined that lead to a feasible solution.

Fundamental physics research aims to gain better understanding of the physics principles and how to describe these. Applicative knowledge, e.g. manufacturing rules and engineering experience, is found in the right hand side.

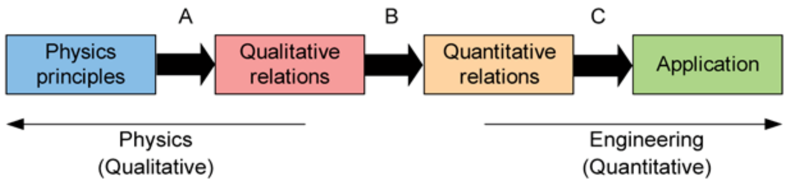

Fig. 1: Knowledge development

Arrow B starts with a functional description of the possibilities and aims to generate quantifiable models. Some representative studies can be found in the application area of qualitative physics to design [6, 7, 9]. Examples for synthesis support for activity C automate the solution generation process, based on a quantitative description of the model. This model can be known explicitly [4, 12] or composed by the software using e.g. grammars [8].

In industry, process C suffers pressure on time and risk to deliver new applications or products from known quantitative knowledge. The relations are present explicitly as analysis methods or implicitly as experience. Only if a new product performance cannot be achieved using known knowledge, a step towards the fundamentals of physics is made to research a new conceptual design, possibly with a new working principle. This means that a new quantitative description of the product has to be made in order to predict the performance. Missing a quantitative relation for an important functional aspect means an inability to predict the products performance, something that is highly undesirably as it introduces risk.

Having synthesis support for activity C will result in faster product development and a better overview of alternatives. It allows expert knowledge to be used in a consistent manner, enabling these experts to spend more time in researching new and innovative concepts. The smart synthesis tools project aims to automate the task of application generation based on quantitative relations and will also explore synthesis towards qualitative physics.

4 Research Topics

The project addresses four research topics that will increase the development efficiency of dedicated synthesis tools.

4.1 Design Knowledge

How to locate, extract and utilize engineering design knowledge during synthesis tool development? The coordination and use of knowledge during the development process will have major impact on the efficiency of the tool. The availability of design knowledge in the design process also determines the content of the synthesis tool. The industrial case handles a design process where experience knowledge is dominant during solution generation and performance analysis.

4.2 Problem Structuring

How can design problems be structured or divided to allow efficient synthesis tool development? Different levels of complexity are identified to allow structuring of the complete design into sub-designs that are less complicated to solve. This also aids the process of searching for strategies to develop a synthesis tool. The industrial case involves designs that are composed of different layers of complexity, where a well defined design structure is of paramount importance for synthesis tool development.

4.3 Large Solution Spaces

How to search and navigate through mathematically complex solution spaces? The case presents a design problem with a high number of parameters and (mathematical and logical) constraints, on a low level of detail. Optimization of these network related problems is a mathematically challenging area.

4.4 Multi-Domain Integration

How to combine mono-domain theories from (qualitative) physics in order to handle interference in multi-domain system design? As product complexity increases and spreads over multiple domains, the systems integration aspect becomes more important: complex multi-domain interferences have to be dealt with in the early stages of the design process and cannot be solved by mono-disciplinary systems. The case concerns system design at architecture level where interference between domains occurs at seemingly unpredictable moments. The coordination and combination of domain knowledge aims at detecting conflicts between subsystems and identifying the cause based on qualitative physics approaches [14].

5 Conclusion

The smart synthesis tools project researches the development process of dedicated synthesis tools in an attempt to bridge the gap between academic research and industrial application. It strives towards a situation where synthesis tools are as common as modelling and analysis software.

The research focuses on the effective use of design knowledge (1), structuring design problems to reduce complexity (2), mathematical techniques to explore the solution spaces efficiently (3) and systems integration aspects to perform synthesis using qualitative physics (4).

Industrial prototypes are developed to provide proof of principle and study the possibilities of synthesis support for industrial applications.

6 Acknowledgement

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Improving Product Development by Design-for-X (DfX) Support

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Abstract
This paper presents possible new business practices that are being created by the PROMISE technologies (PROduct lifecycle Management and Information tracking using Smart Embedded systems). The aim is to facilitate and exploit the seamless flow, tracing, and updating of information about a product in all lifecycle phases, and thereby to enable feedback from post-sales phases to the design phase. Basis for this complete lifecycle management are product embedded information devices (PEIDs) and software tools for decision making and management of product-related knowledge based on field data gathered through a product's lifecycle.

Keywords
Product Development, Design-for-X, Product Lifecycle Management, Field Data, Analysis of Product Behaviour, Product Knowledge

1 Introduction

The main focus of this paper is to present new concepts of supporting DfX by innovative knowledge generation and management. The aspects considered are as follows:

- Capturing field data based on PEIDs from disparate sources and incorporating it into a PLM system.
- Generation of DfX-specific knowledge in order to support decision processes by analysis of component behaviour based on product field data

with respect to the design considerations of various operational and environmental conditions.
- Management of DfX knowledge and its process-oriented provision by augmenting state-of-the-art PLM technology.

To support these innovative processes an IT approach is required that goes far beyond the functionality of currently available PLM systems. This paper describes the aspects of PLM system enhancements and integration technologies that have been essential in order to permit the support of DfX.

The process of knowledge generation in the example described here is based on field data from railway locomotives that are currently in operation. In the field, stresses are applied simultaneously and variably. The resulting interactions are implicitly considered by any analysis using actual field data whereas even the most faithful and rigorous laboratory testing will fail to precisely simulate all field conditions. Hence, product field data is an important source for generating knowledge for similar products if appropriately processed and analysed.

2 Capturing Field Data

This section describes an approach to capturing, aggregating and managing the relevant field data from products in service based on the example of the traction chain of an electric locomotive, which is one of the application scenarios demonstrated within PROMISE. Field data stands here for all kind of gathered data about states, figures and events occurring in a railway system during its life, such as failures during operation and maintenance, work during maintenance, material and energy consumption. Primary LCC-related parameters like man-hours and cost of rework are also included in the field data where possible. The various types of field data that needs to be collected can be grouped in the following categories:
- General; e.g. product identification (article id & serial number)
- Failure announcement; e.g. performance degradation
- Maintenance announcement; e.g. mileage in operation since overhaul
- Fault finding; e.g. failure classification/description
- Maintenance action; e.g. repair activity
- Follow up; e.g. design changes

The field data is gathered from different data sources, which are providing various data on the real behaviour of the product during service:

- Product-embedded Information Devices (PEID): Different sensors distributed over the locomotive are registering real time data on conditions and specific behaviours of the locomotive. These sensors are connected via the vehicle bus to the diagnose system, which is part of the “Train Control and Management System (MITRAC™ TCMS)”. This PEID gathers and evaluates all relevant field data – specific case dependent datasets with over 70 measured characteristics and approximately 3500 malfunction codes – and provides them via ETHERNET, GSM/GPRS or WLAN to the PEID Middleware (ground station).
- Failure Reporting Analysis and Corrective Action System (FRACAS) supported by a Computerized Maintenance Management System (CMMS): FRACAS / CMMS captures every product failure reported by Operators and Maintenance Organizations, in which over 40 failure characteristics can be entered per reported failure
- Other sources providing field data, such as Condition Monitoring / Condition Based Maintenance (CM/CBM) and corresponding tools, Event Recorder, and Inspection Information

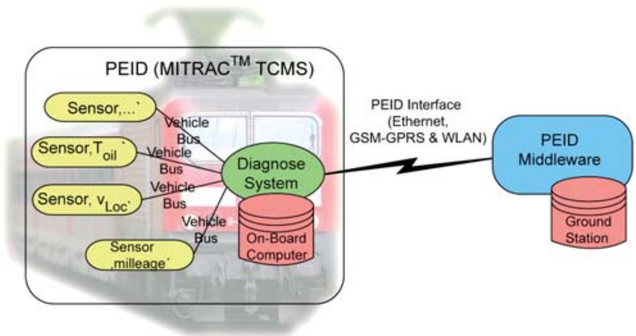

Fig. 1: Automatic monitoring of product behavior using PEID

To get information on the overall product behaviour it is crucial that field data is gathered from both a faulty state of the railway system, related to corrective maintenance, as well as a fault-free behaviour, e.g. related to preventive maintenance tasks – during the whole life time of the product. This goal is achieved within this application scenario mainly by appropriate usage and combination of field data captured by FRACAS and PEIDs. However when the data is gathered, it is essential that the data is kept under constant review for consistency and accuracy. Spurious records should be removed and multiple records for individual incidents consolidated.

Additionally it is inevitable to also consider more static product data from PDM / ERP systems, specific databases (e.g. Engineering Books of Knowledge), intra-/internet sites, and other information sources.

3 Aggregation and Management of Field Data

All captured field data must be stored in such a way that it is safe and easy to disseminate. Therefore all field data shall be merged and managed in one single database as the only source of field data for all 'downstream processes', here specifically the PLM-based DfX Support. This field database is populated by the various sources described above, currently by a manually triggered data transfer. The objectives of this Field Database are:

- Efficient collection of all available product related field data and information, which is currently spread across a number of systems and geographic allocations in one central and commonly accessible database
- Aggregation and categorization of field data and information by means of mathematical and/or statistical methods, to reduce the huge amount of captured field data to a 'reasonable' size for the further processing
- Identification and separation of redundant and non relevant field data and information by means of mathematical and/or statistical methods (e.g. data caused by operational / external reasons, inappropriate product usage, unjustified messages, misspellings, etc.).

The challenge is to collate efficiently this data, which is currently spread across a number of systems and geographic locations and often contains repeated or redundant data, and to ensure its availability in the PROMISE PLM. This is being addressed within this application scenario using the following system concept:

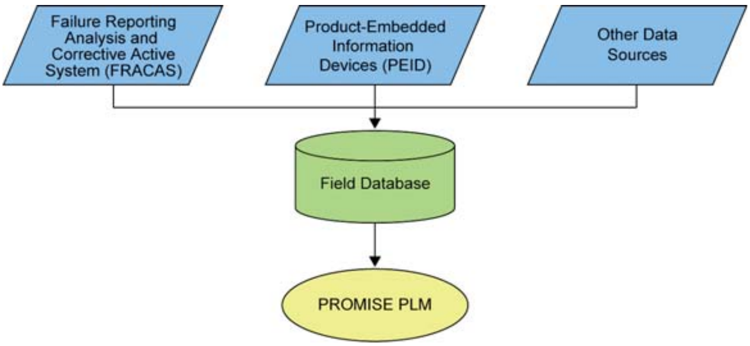

Fig. 2: System concept on field data capturing, management and interface to PLM

The systematic field data collection and performance monitoring of the product in real service through the complete life – which is for a locomotive more than 30 years – is the main element to capture and manage all relevant field data needed for the generation of "Design-for-X" Knowledge.

4 Generation of Design-for-X Knowledge

4.1 Information Generation

In the information generation step, we first select a parameter characterising the design aspect under consideration with respect to which the performance of the different items will be evaluated.

The performances of the item in the different products calculated from field data alone do not provide any information regarding how well the items are performing with respect to the parameter under consideration. To obtain this information the calculated performance should be compared to existing reference or predicted values of the parameter. Should these not exist the experts involved should make a judgment about whether the calculated values correspond to a satisfactory level of performance or not. Information generation is composed of two main steps:

- Calculation of the performances with respect to. the parameter under consideration for each item and over all items, and
- Comparison of the levels of performance of the different items relevant to the selected parameter in order to determine whether or not the different levels of performance are disparate.

4.2 Knowledge Generation

If the performances are disparate a factor impact analysis is pursued and if the performances are not disparate a Pareto analysis is considered.

In the case of disparate performances, the disparity may be caused by one or more factors such as operating conditions, environmental conditions, etc. The objective of factor impact analysis is then to investigate whether or not there are one or more factors that have an influence on the level of performance of the different items.

In the case of non disparate performances, the fact that different items working in different environments and under different conditions have similar performances suggests that probably some intrinsic causes (design, manufacturing, etc.) are behind the level of performance achieved. The objective of Pareto analysis is then to determine the main categories of failures and investigate whether or not the design category is among the main failure categories and in the case where design category is among the main failure categories what the related causes are.

We illustrate the process of generating DfX knowledge from product field data through the consideration of the reliability aspect where MTBF is considered as the main parameter for evaluating the performance of the different items. Factor impact analysis is composed of the following steps:

- Selection of factor(s) for which the impact on the level of performance of the different items with respect to the parameter under consideration will be investigated;
- Definition of clusters representing different levels of performance relevant to the parameter under consideration.
- Calculation of the homogeneity index that measures how much the corresponding values of the factor are similar within clusters and the heterogeneity index that measures how much the corresponding values of the factor are different from one cluster to another.

Pareto analysis is composed of the following steps:

- Selection of a type of categorization of failures e.g. on the basis of their source: design, manufacturing, operation, maintenance, etc.;
- Accounting for severity of failures e.g. by considering a weighting system. Various criteria can be considered to assess the criticality of the different categories of failure. Among them, we can quote direct and indirect maintenance cost, availability, reliability, safety, environmental impact, etc. [1];
- Sorting the (weighted) frequencies of categories of failure from the highest to lowest;
- Determining the main categories of failures i.e. the first categories of failures accounting for more than a certain percentage (e.g. 80%);
- Determining whether the design category is among the main failure categories and if yes what the related causes of failure are.

We can see from the example of Fig. 3, that the main categories of failures are random failure/component wear and design related since together they account for more than 80% of failures. Since the design related category of failures is among the main categories of failures then it is worth investigating the main causes related to the design category of failures.

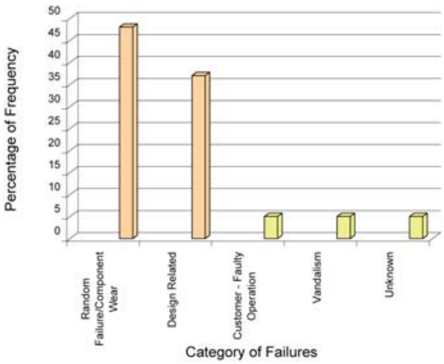

Fig. 3: Pareto analysis applied to the categories of failures

5 PLM-based Design-for-X Support

5.1 PLM Requirements for DfX Support

PLM systems are distributed technological information systems for archiving, administering and providing all product or facility related information in the required quality and at the right time and place. They can be considered as an extension to PDM systems towards a comprehensive approach for product-related information and knowledge management. PLM systems from different vendors are used effectively and efficiently in industry.

Although PLM systems have reached a high level of maturity, they are still not consummate. Analyses have revealed that an out-of-the-box support for Design-for-X processes is not satisfyingly possible. Currently there is no system available that is capable of managing all kinds of field data and relating them to different product configurations, such as as-designed and as-used. Furthermore methodologies for transforming data into DfX characteristics and knowledge are only supported to a limited extent. Generated knowledge cannot be represented to the design engineers in an optimal way [2].

5.2 Data Model for a PLM System

In order to optimally support DfX processes, a data model has been designed which aims at providing product data throughout the whole product life cycle, establishing mechanisms to generate DfX knowledge and representing it systematically. The Unified Modelling Language (UML) has been chosen to describe the data model. It focuses on the classes building up the model as well as the attributes describing their main features and associations illustrating relationships between them. A certain degree of abstraction was required in order to make the data model capable of representing the varying needs of different industrial sectors.

In order to fulfil the product-centric approach, classes describing product types and product instances have been introduced. Product types mainly contain design information from the beginning of life (BOL) phase including bill of materials, CAD models, product variants, material etc. Product instances are used to model proper information on each product at the item instance level. They are characterised by a unique identification (e.g. a serial number) and represent an individual product in the field. Product instances are "derived" from product types in order to ensure that design information related to a physical product can be tracked. The other way around, for a given design the behaviour in the field is traceable as well. Field data – in terms of single values or documents – gathered during product usage can be attached to product instances. The data model also enables the description of main events occurring during a life cycle phase, including details of the resources involved and activities performed.

5.3 PLM System Enhancements

According to the designed data model and knowledge generation methodologies a "Product Data and Knowledge Management" (PDKM) system has been developed by enhancing a commercial PLM system (SAP ECC). Being a central component of the overall approach, the PDKM system aims at systematically integrating and managing data from all lifecycle phases of products. The ultimate goal is to integrate product data of the entire life cycle from different sources and furthermore to support comprehensive analysis based on the integrated data and to enable the enhancement of the operational business with the insights obtained about the products.

The PDKM system is a product-oriented framework with an appropriate analysis of field, environmental and diagnosis data which are presented to the design engineers in different views, e.g. aggregated by a certain product type or averaged over a certain time period. Furthermore information on reliability indices, such as failure rates and mean time between failures of the systems under consideration are accessible via the PDKM system. It also enables tracking of corrective and preventive actions applied to products and interrelate them to the root causes of the faults that have been detected.

Given the capabilities of the PDKM system, design engineers are supported in their decision making processes in order to transform field data into DfX knowledge. Due to the single-point-of entry provided to the relevant information and its role-based representation, decision making processes are accelerated. The results of the knowledge generation process are stored according to a predefined work breakdown structure (WBS). Hence PDKM helps to improve the design of new generation locomotives and close the information loop between the phases of usage and design. A further distinguishing characteristic of PDKM is that it allows integration of data mining tools in order to support analysis of large amounts of field data. An application of these techniques helps to restrict the focus of examination and eases the identification of informative data sets. In addition, the PDKM system expands the scope of configuration management beyond the boundaries of the design and manufacturing phases. Design engineers are able to retrieve up-to-date information about the components of a product and to comprehend the structure of a product at a certain point of time in the product lifecycle. All objects that are managed in the system can be integrated into the workflow, e.g. replacement of components can raise defined events, or abnormal values of field data can result in notifications.

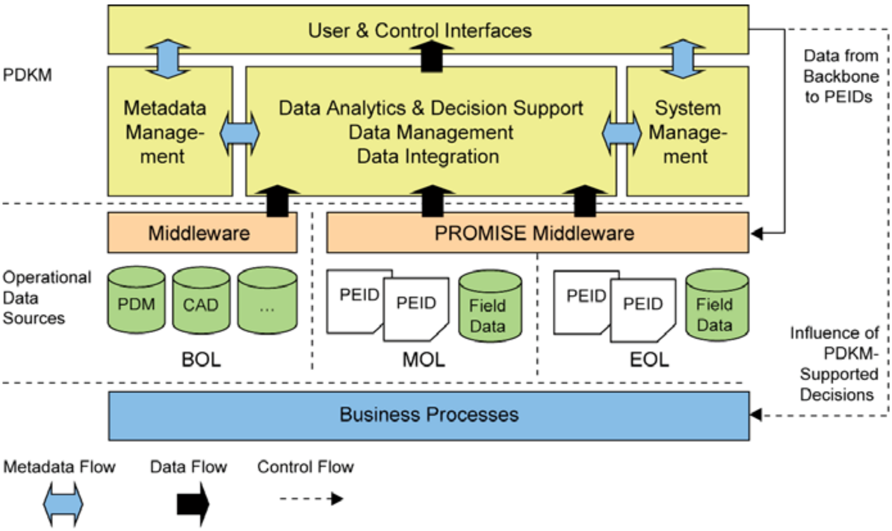

Fig. 4: PDKM Architecture

Figure 4 shows the data flows in the overall PDKM architecture. It indicates that data from PEIDs can be integrated as well as data from other systems. Generated knowledge that is relevant to physical products can be uploaded to the PEIDs.

6 Conclusions

Decisions that have to be made by engineers within complex processes such as the design processes are influenced by numerous parameters. Some of these parameters or at least their correlations are not known to an engineer when he has to take design-relevant decisions. Especially the behaviour of products that are already in operation and that are similar to the new product to be developed can only be suspected due to a lack of relevant field data and methods for their evaluation.

To overcome these problems methods and tools for capturing, analysing and evaluating field data have to be introduced in order to improve complex processes such as DfX and to ensure a higher quality of decision making by provision of a more substantiated information basis. Since the relevant data the engineers need for their work are distributed over several systems and databases, a logical integration and a single access point for the user have to be provided. In this paper the relevant aspects for a DfX support are described. This includes the process of capturing and analysing field data, the generation of product-related knowledge and the necessary extension of the state-of-the-art PLM technology. The main focus is on algorithms for generation of DfX knowledge and on management and provision of all relevant information related on products.

7 Acknowledgements

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Looking at “DFX” and “Product Maturity” from the Perspective of a New Approach to Modelling Product and Product Development Processes

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Abstract
Base of this contribution is a quite new theoretical approach to modelling products and product development processes developed by the author and his team: “Characteristics-Properties Modelling” (CPM) and “Property-Driven Development” (PDD), respectively. This approach is able to give extended or new explanations for some issues important in product development/engineering design. In this contribution the terms “Design for X” (DFX) and “(Degree of) Product Maturity” are investigated both of which are important issues in practice, but until today only weakly related to the theoretical foundation of product development/engineering design.

Keywords
Design theory and methodology, DFX, product maturity

1 Introduction

Theories and models of technical products and product development processes have been in the focus of scientific work for roughly 40-50 years. Today, they are increasingly relevant also in industrial application because they are vital elements of current strategies such as concurrent/simultaneous engineering, “Design for X” (DFX = generic term for DFM, DFA, DFQ, DFC[1], ...), “front loading”, i.e. bringing a maximum of considerations concerned with later phases of the product life-cycle up as early as possible

[1] DFM/DFA/DFQ/DFC – Design for Manufacturing/Assembly/Quality/Cost.

in the process, thus generating a more steep and even gradient of product maturity during development. These strategies are supported by an increasing number of more and more sophisticated computer models and tools (e.g. CAD, CAE, PDM, PLM[2], ...), culminating in the "virtualisation" of the entire product development and product creation process ("virtual product development", "digital factory"). All the strategies, methods and tools mentioned serve the ultimate purpose of helping companies meet present challenges such as cutting cost and (development) time, at the same time raising product quality.

This contribution is based on a new approach to modelling products and product development processes – called "Characteristics-Properties Modelling" (CPM) and "Property-Driven Development" (PDD), respectively – and tries to show that this new approach can shed a new light on some of the strategies mentioned, particularly on "DFX" and "product maturity".

The basic approach of CPM/PDD was explained in a couple of earlier publications (e.g. [1]), a book is in preparation. In order enable reasoning about "DFX" and "maturity" on that base it is, however, necessary to give a brief recapitulation of the fundamentals of the CPM/PDD approach first.

2 A new Approach on Product and Process Modelling: Characteristics-Properties Modelling (CPM) and Property-Driven Development (PDD)

2.1 Fundamentals

The CPM/PDD approach stands in the tradition of "Design Theory and Methodology" (DTM). It has the following goals:

- To build upon and consolidate the results and the knowledge created in design theory and methodology so far. This includes concepts originating in Europe (e.g. [2 – 5]) and in the USA (e.g. Axiomatic Design [6, 7]).
- To integrate many existing models and strategies into a common framework (e.g. DfX, as will be discussed).
- To explain some still open theoretical and practical questions.
- To re-define the role of computer (but also other) methods and tools in product development based on a more solid scientific foundation, thus giving concrete hints for the further development of methods and tools.

[2] CAD/CAE – Computer Aided Design, Engineering. PDM/PLM – Product Data/ Life-Cycle Management. CAX – Computer Aided "Anything".

- To bring design theory and methodology closer to the way practitioners think and proceed in product development.

Characteristics-Properties Modelling (CPM) is the ***product*** modelling side of the new approach. Based on this, Property-Driven Development (PDD) explains the ***process*** of developing and designing products.

Both are mainly based on the distinction between characteristics (in German: "*Merkmale*") and properties ("*Eigenschaften*") of a product:

- The ***characteristics*** (formally denoted $\mathbf{C}_i$ later on) describe the structure, shape, dimensions, materials and surfaces of a product ("Struktur und Gestalt", "Beschaffenheit"). They can be directly influenced or determined by the development engineer/designer.
- The properties (Pj) describe the product's behaviour (e.g. weight, safety and reliability, aesthetic properties, but also things like "manufacturability", "assemblability", "testability", "environmental friendliness", cost). They can ***not*** be directly influenced by the developer/designer.

The characteristics are very similar to what is called "internal properties" in [4] and what Suh [6, 7] calls "design parameters". The properties as introduced here are related to "external properties" according to [4] and to "functional requirements" according to [6, 7].

To be able to handle characteristics and properties – literally thousands of them in complex products – and to keep track of them in the development process they have to be structured. Fig. 1 shows the basic concept as it is discussed in CPM/PDD:

- On the left of fig. 1 a fairly obvious proposition for the (hierarchical) structuring of characteristics is given following the parts' tree of a product. It complies with usual practice, but also links our considerations to data structures of CAX-systems. Different criteria of structuring characteristics are theoretically possible, but not discussed here.
- On the right of fig. 1 a proposition for the top-level "headlines" of structuring properties is presented which is based on criteria determined by the typical product life phases but at the same time reflects frequently discussed issues in product development/engineering design. Again, different methods of structuring properties (different "headlines") could be theoretically imagined, but are not discussed here.

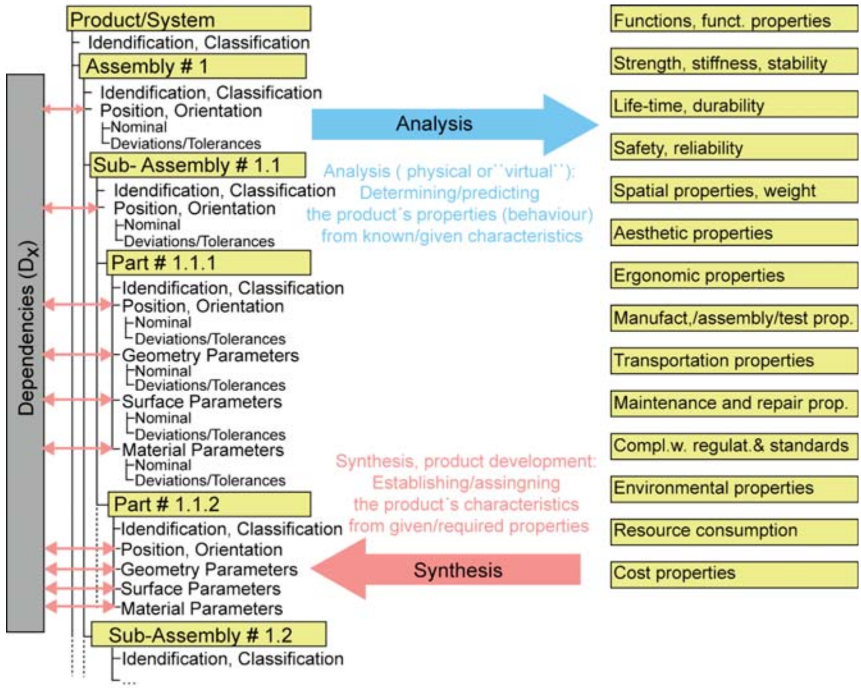

Fig. 1: Characteristics (left) and properties (right) with analysis and synthesis as the two main relations between the two

Of course, also the properties should be structured more deeply by further decomposition below the “headlines”. The author is, however, convinced that the further structuring of properties as well as the importance are always specific to individual industries (product classes), often even specific to individual companies and are even time-dependent. In this relatively short paper it is not possible to go into further details.

On the characteristics (left) side of fig. 1 an additional block is drawn which represents dependencies between characteristics ($\mathbf{D}_x$). Any development engineer/designer is very familiar with these dependencies, e.g. geometric or spatial dependencies (which today can be captured and administered by parametric CAD-systems), but also concerning fits, surface and material pairings, even conditions of existence.

Finally, fig. 1 introduces the two main relations between characteristics and properties:

- ***Analysis:*** Based on known/given characteristics (structural parameters) of a product its properties are determined (its behaviour is determined), or – if the product does not yet exist in reality – predicted. Analyses can, in principle, be performed by experiments (using a physical model/ mock-up or a prototype) or "virtually" (by calculation and/or using digital simulation tools).

- ***Synthesis:*** Based on given, i.e. required, properties the product's characteristics are established and appropriate values assigned. Synthesis is the main activity in product development: The requirements list is in principle a list of required properties and the task of the development engineer/designer is to find appropriate solutions, i.e. an appropriate set of characteristics to meet the requirements to the customer's satisfaction. Of course, the requirements list may already contain characteristics, but then it predefines certain solution patterns, i.e. specific partial sets of characteristics, right from the beginning (at least implicitly).

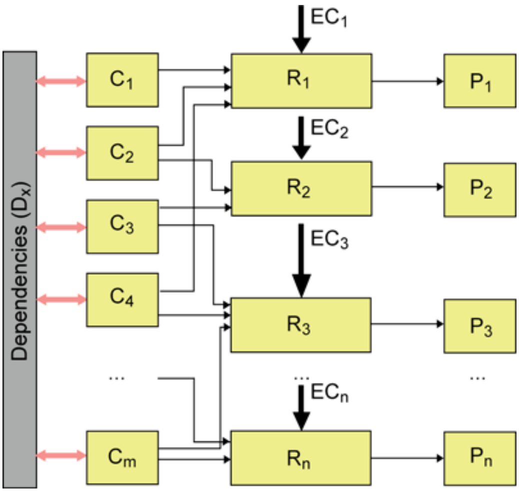

Fig. 2: Basic model of analysis

In the CPM approach (as well as in PDD based upon it) analysis and synthesis as the two main relations between characteristics and properties are now modelled in more detail, in principle following a network-like structure. Fig. 2 and fig. 3 show the two basic models for analysis and synthesis, respectively. In order to keep considerations simple, both on the side of the characteristics (**C**$_i$) and on the side of the properties (**P**$_j$ or **PR**$_j$, respectively) a simple list (or vector) structure is displayed.

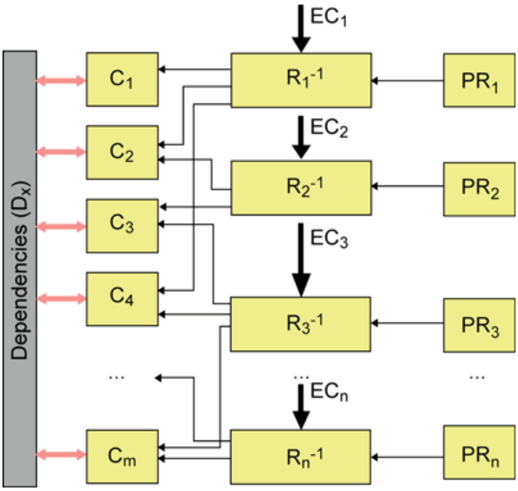

Fig. 3: Basic model of synthesis

The expressions used in figures 2 and 3 and in all subsequent figures have the following meaning:

C_i:	Characte ristics („*Merkmale*")	**R_j, R_j^{-1}:**	Relations between characteristics and properties
P_j:	Properties („*Eigenschaften*")		
PR_j:	Required Properties	**D_x:**	Dependencies ("constraints") between characteristics
EC_j:	External conditions		

2.2 Analysis

Models, methods and tools to realise the relation-boxes (**R_j**) shown in fig. 2 can be based on physical objects (phys. models, phys. mock-ups, prototypes of components or the whole product, components or product in finalised state) or non-physical models (mental models, mathematical or graphical models, computer models). Roughly sorted from "soft" to "hard":

Note that computer tools can be based on many different concepts: physical models turned into mathematical models and numerically solved (the most common case), but also rule-based strategies, "fuzzy logics", semantic or neural networks, case-based reasoning, …

• Guesswork, estimation • Experience • Interrogation (e.g. customers) • Physical tests/experiments	• Tables, diagrams (= formalised experience & experimental knowledge) • Conventional/simplified calculations • Computer tools

Once the product exists (i.e. when the product's characteristics $\mathbf{C}_i$ are physically realised) and operates, the analysis of its properties/behaviour ($\mathbf{P}_j$) according to fig. 2 can be performed by testing and measuring. In this case the product itself is the representation of the relations ($\mathbf{R}_j$).

During product development, however, when there is not yet a finished product, its properties can only be analysed by means of appropriate methods and tools which are based on (physical or non-physical) models. They are exactly what the relation-boxes ($\mathbf{R}_j$) in fig. 2 stand for; their purpose is to tell about the influences of relevant characteristics ($\mathbf{C}_i$) on the respective properties ($\mathbf{P}_j$), thus ***predicting*** the properties given at that moment.

Using computer models and tools to model a product and analyse its properties is today called "virtual product (modelling)", see Spur & Krause 1997. Against the background of the CPM approach, the ***completely virtual product (model)*** can now be defined as an approach where computer tools are used to ***determine/predict all relevant properties*** of a product which, consequently, does not have to exist (yet) in the physical world.

The basic product model according to fig. 2 (and also fig. 3) displays one more element which is particularly important here: The determination/ prediction of every product property via an appropriate model, method and tool must be performed with respect to certain external conditions ($\mathbf{EC}_j$). They define the framework in which the statement about the respective property is valid. It is these external conditions which will be the key to a new explanation of "Design for X" (DFX) shown in section 3.

2.3 Synthesis

Looked upon from a formal point of view, synthesis is "just" the inversion of analysis (Figure 3): Based on given properties – which are now ***required properties*** $\mathbf{PR}_j$ – the product's characteristics ($\mathbf{C}_i$) are to be established and/ or assigned. In engineering, the only way to do synthesis is to use appropriate synthesis methods and tools which the "inverted relation-boxes" ($\mathbf{R}_j^{-1}$) in fig. 3 stand for. Again sorted from "softer" to "harder" methods and tools:

- Human genius[3]
- Association – technical or biological patterns ("bionics")
- "Experience" (= association based on past cases?)
- Catalogues, stand. Solutions
- Collection of rules
- Methodical/systematic approaches (combining several of the above)
- Inverted conventional/simplified calculations
- Computer tools

Even the most simple synthesis model shown in fig. 3 displays the nature of conflicts, fig. 4: Different required properties demand the same characteristics to be determined differently.

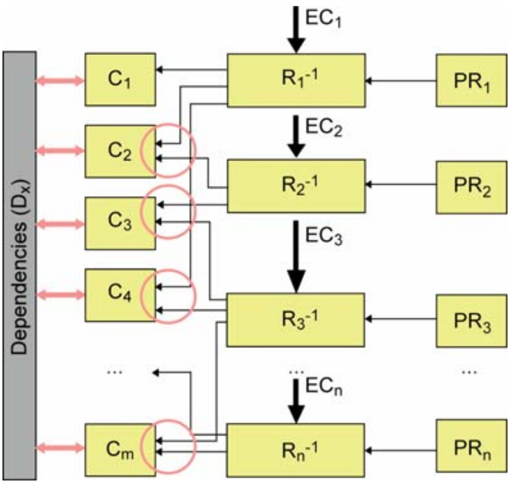

Fig. 4: Conflicts in synthesis: Different properties try to establish/assign the same characteristics differently

2.4 Solution Elements, Solution Patterns

The definition and utilisation of solution elements, solution patterns, etc. is very important in practical product development/design, because it enables the re-use of knowledge and is the base of product modularisation. Seen from the perspective of the CPM approach introduced here, a solution pattern is nothing else than an aggregation of characteristics ($\mathbf{C}_i$) and properties ($\mathbf{P}_j$) with known relations ($\mathbf{R}_j$) between the two, fig. 5.

The use of solution elements/patterns does not only enhance standardisation, but is also attractive for another reason: If characteristics ($\mathbf{C}_i$), prop-

3 The same as (quick) association?

erties ($\mathbf{P}_j$) and relations between them ($\mathbf{R}_j$) are all known, then this "knowledge" can be used in ***both*** directions, i.e. for analysis as well as for synthesis (e.g. searching for solution elements/patterns with required properties as an entry point).

Solution patterns can also be stored in computers: Variant programmes, pre-defined features and feature libraries and – as a quite recent extension of CAD making even a bigger step from the characteristics to the properties side – "Knowledge-Based Engineering" (KBE) are nothing else than digital representations of solution elements/patterns as introduced here.

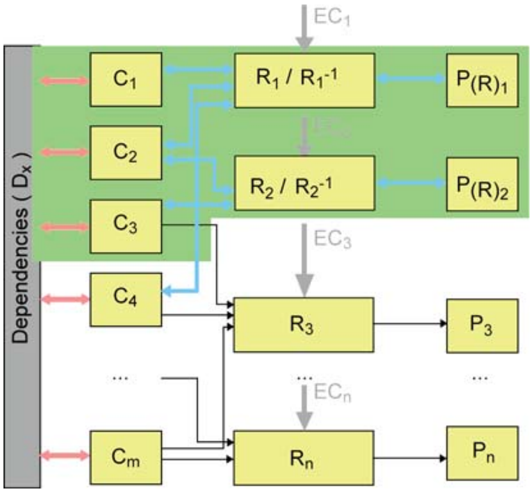

Fig. 5: Schematic representation of a solution element/pattern

2.5 Property-Driven Development (PDD)

Based on the considerations on the new approach to modelling products (CPM, sections 2.1 to 2.4), now the consequences for the modelling of product development processes are presented.

The product development process can be seen as an activity which, in principle ("strategically"), follows the synthesis model according to fig. 3 but has in between ("tactically") many analysis steps according to fig. 2.

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1 Synthesis

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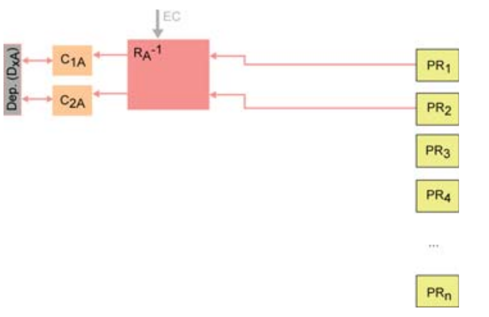

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2 Analysis

Notes:

- Always all properties are analysed – including those that did not stimulate the initial synthesis step(s)
- In early stages, however, it may not yet be possible to determine all of them.

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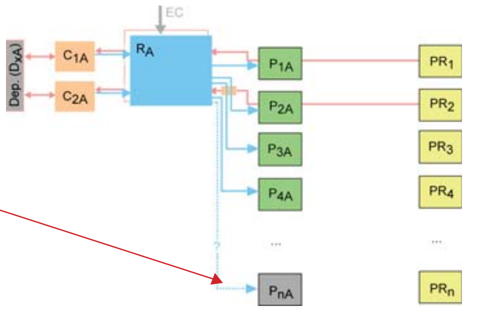

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3 Individual deviations

Note: During the process it may be necessary to modify the requirement (**RPj**) – e.g. in order to consider additional properties that only come up later.

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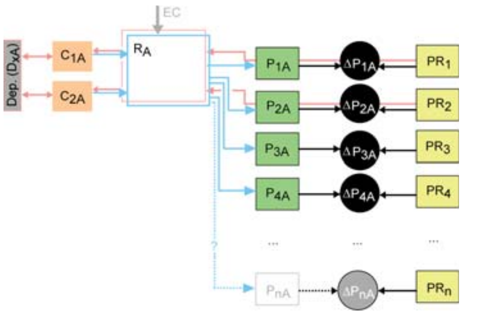

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4 Overall evaluation

Note: Results of overall evaluation are actual driver of the process.

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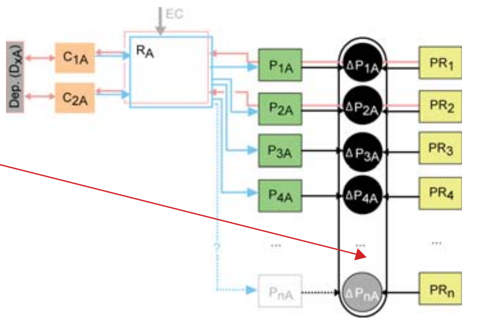

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Fig. 6: PDD-scheme of steps in the 1st cycle ("cycle A") of product development

During the process – in every synthesis step – ever more characteristics of the product are established and their values assigned, in parallel – by means of the analysis steps – ever more and ever more precise information of the product's properties/behaviour is generated.

Fig. 6 gives a schematic overview; for reasons of space, only the first synthesis-analysis-evaluation cycle ("cycle A") is shown. The first cycle of product development ("cycle A") runs as follows:

1. The product development process starts with a list of requirements. This list is in PDD represented by the required properties (PRj, Soll-properties). In step 1 the development engineer/designer starts from some of the properties and establishes the first major characteristics (Ci) of the future solution (synthesis). In practice this is usually done by adopting partial solutions known from previous designs (= solution elements/patterns, see fig. 5).
2. In step 2 the current properties (Pj, Ist-properties) of the present solution state are analysed, based on the characteristics currently established. In this analysis step not only those few properties, which went into the first synthesis step, are considered, but all of the relevant properties (if possible – if there are too few characteristics defined yet, then it may be difficult to reason on some of the more complex properties).
3. Next (step 3), the results of this analysis are used to determine the deviations of the individual Ist-properties against the required (Soll-) properties, the result of the comparison (ΔPj) representing the shortcomings of the current design.
4. The development engineer/designer now has to run an overall evaluation (step 4): Extract the main problems and decide how to proceed, i.e. pick out the property or properties to attack next and select appropriate methods and tools for the subsequent synthesis-analysis-evaluation cycle.

All subsequent cycles of product development/design ("B", "C", …) are analogous, but not shown in fig. 6 anymore. From one cycle to the next as a result of each synthesis step ever more characteristics are established and their values assigned, i.e. the structural description of the solution gets more and more detailed. The analysis steps of all cycles basically all deal with the same properties over and over again – but with a modified and/or extended set of characteristics. In consequence, the analysis methods and tools have to switch from rough to ever more exact ones enabling an ever more precise determination/prediction of properties along the process. The product development process itself is controlled (driven) by the overall evaluation of the current "gap" between *Soll*- and *Ist*-properties at the end of each cycle.

In a strongly abstracted representation, the product development process can be seen as a control circuit, fig. 7, where

- the required properties ($\mathbf{PR}_j$) are equivalent to the reference value,
- the actual/current properties ($\mathbf{P}_j$) are both output and feedback value,
- current deviations between required and as-is properties ($\mathbf{\Delta PR}_j$) correspond to the current "error",
- the characteristics ($\mathbf{C}_i$) are analogous to the input value and where
- the external conditions ($\mathbf{EC}_j$) play the role of disturbances (which is a quite "interesting" analogy!).

In terms of the structure of the control circuit

- the synthesis methods and tools ($\mathbf{R}_j^{-1}$) act as the "actuator",
- analysis methods and tools ($\mathbf{R}_j$) are the "sensors" and
- the overall evaluation of current deviations between required and as-is properties (called "Eval." in fig. 7) plays the role of the control unit.

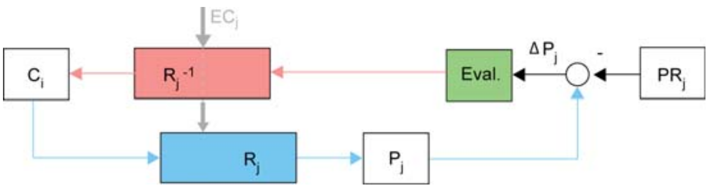

Fig. 7: Abstract representation of product developmentas a control circuit

2.6 Termination of the Product Development Process

The product development/design process terminates if and when

- all characteristics needed for manufacturing and assembly of the product are established and assigned ($\mathbf{C}_i$),
- all (relevant) properties can be determined/predicted ($\mathbf{P}_j$),
- with sufficient certainty and accuracy, and
- all determined/predicted properties are close enough to the required properties ($\mathbf{\Delta P}_j \rightarrow \mathbf{0}$).

3 Design *for* X (DFX) and Design *of* X

As has already been stated in the introductory section 1, "Design for X" (DFX, with "X" = strength, manufacturing, assembly, service, recycling, cost, etc.) is an important strategy especially in engineering design practice. Until now, however, the link between DFX and the engineering design theory is comparatively weak, and DFX methods are rather added to and not really embedded in design methodology.

This section tries to show a novel theoretical background of DFX methods and tools, based on the CPM/PDD product and process modelling approach explained in the previous section, building upon but also extending earlier findings [1, 8]. The aim is to systematise and integrate DFX methods and tools into design theory and methodology and to generate new ideas for their further development. Additionally, it will be shown that with the theoretical background of CPM/ PDD, “Design ***for*** X” can easily be extended to “Design ***of*** X”.

The core of considerations is that any DFX method is a concretisation of a “relation box” ($\mathbf{R}_j$, $\mathbf{R}_j^{-1}$) between product characteristics and a particular property, the “X-property” (see fig. 2 and 3). There are analytical DFX methods ($\mathbf{R}_j$) which determine the “X-property” of the product from given product characteristics and will eventually lead to a comparison with the required “X-property” of the product, thus enabling statements about its “X-ability”. But there are also synthetical DFX methods ($\mathbf{R}_j^{-1}$) which are used to establish, assign or modify characteristics of the product in accordance with its required “X-property”.

As was already pointed out at the end of section 2.2, the determination/ prediction of a product property via an appropriate analysis method/ tool and also the establishing/assigning/modifying of product characteristics from required properties via a synthesis method/tool must be performed with respect to certain external conditions ($\mathbf{EC}_j$). It can now be stated that the external conditions ($\mathbf{EC}_j$) relevant for the analysis or synthesis of the product are a result of the properties of the X-system ($\mathbf{P}_X$) which the product “meets” in the life-phase under consideration, e.g.: The external conditions to analyse or synthesise good manufacturing properties of the product are related to the properties of the manufacturing system.

This idea is very closely related to the concept of so-called relational properties introduced in [9]; the main difference is that the model presented here can be more strictly formalised and that it is derived in a relatively systematic way from the basic CPM/PDD approach.

The idea of regarding external conditions ($\mathbf{EC}_j$) as a result of the properties of the neighbouring X-system ($\mathbf{P}_X$) also implies that they are the outcome of a separate product model, which describes the behaviour of the X-system (not the product being developed/designed with regard to that X-system). This X-system now has its own set of characteristics ($\mathbf{C}_X$), which determine those very same properties.

These considerations lead to the extended DFX concept shown in **fig. 8, top row**, which explicitly displays the X-system itself as an artefact ("product") that – in vertical direction – can be described by exactly the same characteristics-properties structure as the product to be developed/ designed with regard to the properties of the X-system.

In this way, the CPM/PDD approach produces inter-linked self-similar models of the product being developed/designed and of the several X-systems which have to be considered in DFX.

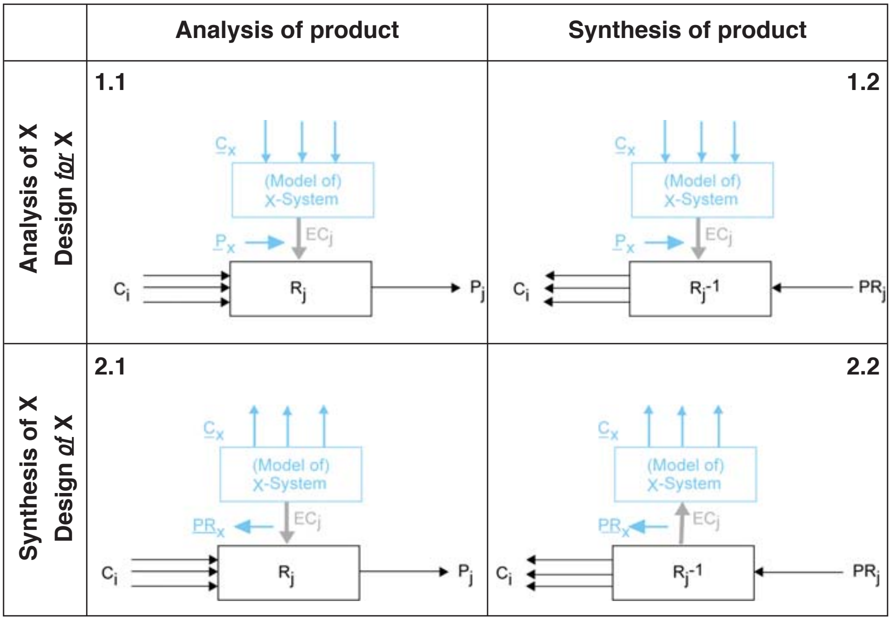

Fig. 8: Extended model of "Design ***for*** X" (top row) as well as "Design ***of*** X" (bottom row) in combination with product analysis (left column) and product synthesis (right column)

Until now the external conditions (**EC**$_j$) relevant for the analysis or synthesis of the product were linked to the properties of the X-system (**P**$_X$) which can be determined by ***analysing*** the X-system.

But we now can also reverse the arrows in the (vertical) X-system's model which would lead to ***synthesising*** the X-system, **fig. 8, bottom row**. This view is not "Design ***for*** X" anymore, but rather "Design ***of*** X". For the example "X = manufacturing" this means that the development of a product and the manufacturing system is done simultaneously (case 2.2).

In summary, the CPM/PDD approach systematically leads to four cases of "Design for X" as well as "Design of X" (see fig. 8 for graphics):

1.1 From given product characteristics ($\mathbf{C}_i$), determine product property ($\mathbf{P}_j$) with regard to known external conditions ($\mathbf{EC}_j$) which are determined by given properties of the X-system ($\mathbf{P}_X$). This case represents the classical ***analytical*** "Design for X" procedure.
1.2 Starting from required product property ($\mathbf{PR}_j$), establish/assign/modify appropriate product characteristics ($\mathbf{C}_i$) with regard to known external conditions ($\mathbf{EC}_j$) determined by given properties of the X-system ($\mathbf{P}_X$). This is the classical ***synthetical*** "Design for X" procedure.
2.1 From given product characteristics ($\mathbf{C}_i$), determine product property ($\mathbf{P}_j$) and simultaneously appropriate external conditions ($\mathbf{EC}_j$). These define required properties of X-system ($\mathbf{PR}_X$) which have to be realised by establishing/assigning/modifying the characteristics of the X-system ($\mathbf{C}_X$). This is the first "Design ***of*** X" case which is "analytical" in the product domain, but "synthetical" in the X-system domain. An example would be to introduce a new technology and a new manufacturing system for a given/known product.
2.2 Starting from required product property ($\mathbf{PR}_j$), establish/assign/modify product characteristics ($\mathbf{C}_i$) and at the same time appropriate external conditions ($\mathbf{EC}_j$). These define required properties of X-system ($\mathbf{PR}_X$) which have to be realised by establishing/assigning the characteristics of the X-system ($\mathbf{C}_X$). This is the second (and most challenging) "Design ***of*** X" case which is "synthetical" in both the product and the X-system dom ain. An example would be developing/designing a new product and a new technology/manufacturing system simultaneously.

In practice, probably mixtures of these four cases will occur. A first application of this concept, again for the example "X = manufacturing", was presented in [10]; it is quite closely related to propositions made by Ueda in [11] for layout planning of manufacturing systems.

4 Measuring the (Degree of) Product Maturity

The term "maturity" or "degree of maturity" is being increasingly discussed in industrial practice as well as in academia. In most cases the maturity of ***processes*** is addressed (e.g. using the so-called Capability Maturity Model, CMM, see [12]). In this section a completely different, more engineering-related approach is presented which deals with ***product*** maturity. The background is the PDD process concept presented in section 2.5 where the overall evaluation of current product properties was introduced as the main control unit of the whole product development/design process.

The concept proposes to measure the (degree of) product maturity at a given time t in the product development process via two components:

- one maturity value related to the product characteristics ($\mathbf{M_C}$) and
- one maturity value related to the product properties ($\mathbf{M_P}$).

The following explanations use the formal expressions:

$\mathbf{P_j}$:	As-is-property (*Ist*-property) j
$\mathbf{PR_j}$:	Required property (*Soll*-property) j
$\mathbf{N_{Ci}}$:	Number of characteristics already established
$\mathbf{N_{Cm}}$:	Number of characteristics necessary to build product
$\mathbf{M_C}$:	Characteristics-related maturity
$\mathbf{M_{Pj}}$:	Properties-related maturity (only property j)
$\mathbf{M_P}$:	Properties-related maturity (all properties)
$\boldsymbol{\varepsilon_j}$:	Confidence factor of determining property j ($0 \leq \boldsymbol{\varepsilon_j} \leq 1$)
M:	"Total" maturity

Characteristics-related Maturity M_C:

$\mathbf{M_C}$ measures the number of product characteristics already established/assigned in relation to the total number of characteristics necessary to build the product ("completeness of product definition").

$$M_C(t) = \frac{N_{Ci}(t)}{N_{Cm}} \quad (1)$$

During the product development/design process, i.e. before the design is finished, it is, of course, not possible to do an exact determination of the total number of characteristics necessary ($\mathbf{N_{Cm}}$, denominator of eq. (1)). Most companies will, however, have quite some experiences from past projects that would allow them to make fairly good estimations. One easily realisable method would be counting the number of existing and released component files in the CAD- or PDM-system and relating it to the number of components in the "empty" parts structure which usually is given right from the start of the project.

Properties-related Maturity M_P:

$\mathbf{M_P}$ measures the current state of one or more/all product properties in relation to the required properties ("compliance of present state of solution with requirements").

For one single property $\mathbf{P_j}$:

$$M_{Pj}(t) = \frac{P_j(t)}{PR_j} \cdot \varepsilon_j \tag{2}$$

Eq. (2) implies three assumptions:

- The property in question ($\mathbf{P_j}$) is "countable".
- The property improves with ascending values ("the bigger, the better").
- "Over-fulfilling" a requirement is definitely allowed, even "rewarded", as this case will result in $\mathbf{M_{Pj}} > 1$.

If the first assumption is not valid, then a suitable transformation method must be found (e.g. defining measurable classes). If the second or the third assumption (or both of them) are not valid, modified mathematical formulations have to be substituted which shall not be explained in detail here.

As a quite fundamental element, eq. (2) contains a "confidence factor" $\boldsymbol{\varepsilon_j}$. The basic idea is to assign $\boldsymbol{\varepsilon_j}$ to the method/tool used to determine the property in question with values of $\boldsymbol{\varepsilon_j}$ between 0 and 1:

- In early phases of product development, where still only few characteristics are established/assigned, relatively simple and less accurate analysis methods/tools have to be used; these would have low values of $\boldsymbol{\varepsilon_j}$.
- In later phases, where most or all of the details are available, quite elaborate and accurate analysis methods can be implied that deliver highly exact results and, therefore, can be assigned with high values of $\boldsymbol{\varepsilon_j}$. (possibly up to $\boldsymbol{\varepsilon_j} \approx 1{,}0$ with extensive physical testing of real products).

A product must, of course, satisfy not only one requirement (one required property) but a multitude of them (j = 1 … n). Therefore, in order to measure the overall properties-related maturity some sort of superimposing all the individual $\mathbf{M_{Pj}}$ values must be implied.

The most simple approach to calculate the properties-related maturity over all properties ($\mathbf{M_P}$) is forming the mean value:

$$M_P(t) = \frac{1}{n} \cdot \sum_{j=1}^{n} M_{Pj}(t) = \frac{1}{n} \cdot \sum_{j=1}^{n} \left[\frac{P_j(t)}{PR_j} \cdot \varepsilon_j \right] \tag{3}$$

Weighting factors could be considered (e.g. according to the weighting of requirements in a requirements management system which may exist anyway) but, for reasons of simplicity, is not shown here.

"Total" Maturity M:

The "total" maturity of the product at a given time t in the product development/design process is now calculated via the characteristics-related maturity ($\mathbf{M_C}$) and the (overall) properties-related maturity ($\mathbf{M_P}$):

$$M(t) = M_C(t) \cdot M_P(t) = \frac{N_{Ci}(t)}{N_{Cm}} \cdot \frac{1}{n} \cdot \sum_{j=1}^{n} \left[\frac{P_j(t)}{PR_j} \cdot \varepsilon_j \right] \tag{4}$$

To summarise, fig. 9 graphically displays the proposed approach to determine the (degree of) product maturity at a given time t in the product development/ design process within the framework of the CPM/PDD.

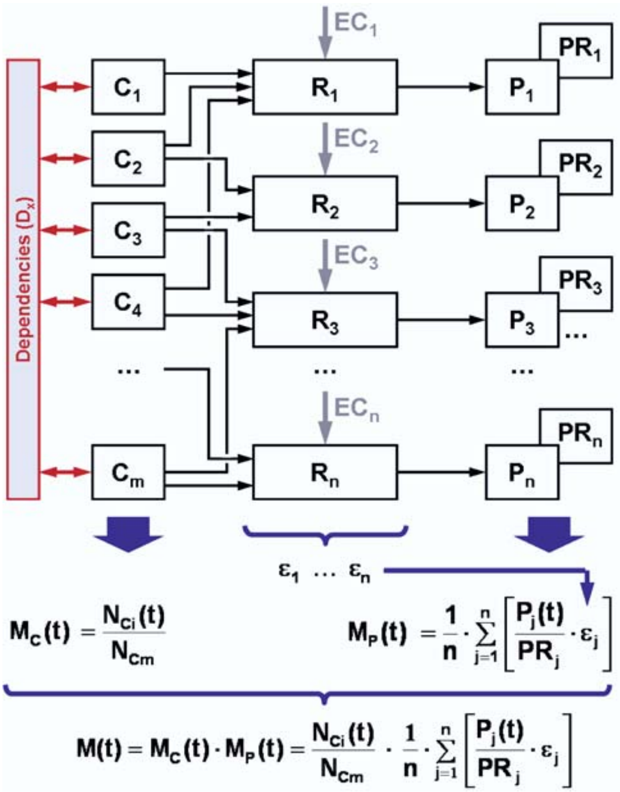

Fig. 9: Scheme of determining the (degree of) product maturity within CPM/PDD

5 Conclusions

This contribution presents "Characteristics-Properties Modelling" (CPM) and "Property-Driven Development" (PDD) and, based on it, tries to give extended or new explanations for the terms "Design for X" (DFX) and "(Degree of) Product Maturity", both of which are important issues in practice, but until today only weakly related to the theoretical foundation of product development/engineering design.

Even if the approaches and conclusions presented in this paper may be regarded as a very particular view and if results still have to be discussed, the author would like to transfer a general message:

One important part of the future of product development in research and development is to develop an integrated view on the vast amount of knowledge (theories, models, methods, tools) that already exist and to relate these to one another in order to provide scientists and practitioners with a consolidated concept fit for the 21st century.

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Support of Design Engineering Activity for a Systematic Improvement of Products

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Abstract
Design research in the past few years has revealed several lacks of the “classical” design methodologies. The predominantly systematic-analytic, on deductive procedure based design methodologies are still basis for research and education but are judged to be little applicable in a real designing environment [4, 5]. Hence, the trend of design research has put the engineer in the middle of focus as a problem-solving individual. This paper introduces an approach for a successful proceeding in solving complex engineering problems based on the established Contact and Channel Model (C&CM). The problem solving process begins with a C&CM system analysis providing the information needed for understanding the relations between form and function on the adequate level of abstraction. Through a widespread understanding, a basis for creative, intuitive filling of the gaps in the problem ground is created.

Keywords
Problem Solving, Product Development Process, Design Model

1 Introduction

The industry needs to improve the design process due to the drastic reduction of product development time. Increasingly shorter product life cycles lead research to develop new strategies for the quick and efficient solving of constructive problems. The call for a target-oriented and reliable solution of problems which includes the troubleshooting of errors as well as and the planning of development activity itself is in the focus of design process researchers since the 1950s. The time of “bottleneck in design engineering”

[18] bore the "classical" design engineering methodologies e.g. like VDI 2221 [17]. These methodologies are still basis for research in design engineering and are the basis for design education.

Engineering is a highly complex activity that is based on many cognitively and psychologically founded mental processes. In addition, the complex structure of products, their large number and variety make it impossible to keep overview over the whole knowledge area of engineering. These two research domains of design are faced for example through the introduction of the idea of systems engineering into design methodology by e.g. Ehrlenspiel [8]. The approach aims at the reduction of complexity by means of transferring the problem onto a more general and abstract level. On the other side, big research effort is heading on improvement and support of the human problem solving activity which has become the central aspect of design engineering methodology [4, 5, 8, 9, 11]. Abstraction is a core competence for a successful problem solving ability of any engineer and is basis for many methods in design engineering. E.g. TRIZ abstract the solution of many patents and thus makes them available for the solution if new problems [14]. This paper explores a new strategy to support engineers in their problem solving activity. The C&CM provides a systematic way to anchor "systems thinking" and is methodologically based on results of latest expertise in design methodology concerning the human problem solving activity.

Based on the approach a procedure of applying the C&CM is introduced and explained by means of an example out of a current industry project conducted at the Institute for Product Development IPEK at University Karlsruhe (TH). This facet of research fits into the holistic concept for product development of the IPEK. Together with the SPALTEN [1] as guide for a systematic problem solving process and the model of the product life cycle e.g. in [3] as the superior process model of product development the C&CM product model provides a systematic to describe the objects of the product development process.

Objective of the research effort is the support of engineers in the creative phase of the constructive problem solving process. The goal is to improve solution quality within lean time due to requirements of the highly dynamic world of innovation.

2 Method

2.1 Contact and Channel Model

Building up models; internal (mental) and external (e.g. CAD or sketching), is a vital means for engineers to reduce the complexity of design problems. Models provide the intrinsic information necessary for the solution of the problem and omit the information dispensable. The act of building up a model of the problem is thus basic for design engineering. How engineers formulate their problem strongly determines how they search for solutions [16]. Using the Contact and Channel Model (C&CM) supports the internal and external problem modelling. The visualisation of functions through their allocation on the visible shape helps building up an abstracted model. The idea of the C&CM arose through the question of why experienced designers and also mechanics have the ability to understand the functionality of a system much more quickly than inexperienced freshmen. Experienced successful designers have an excellent internal problem representation.

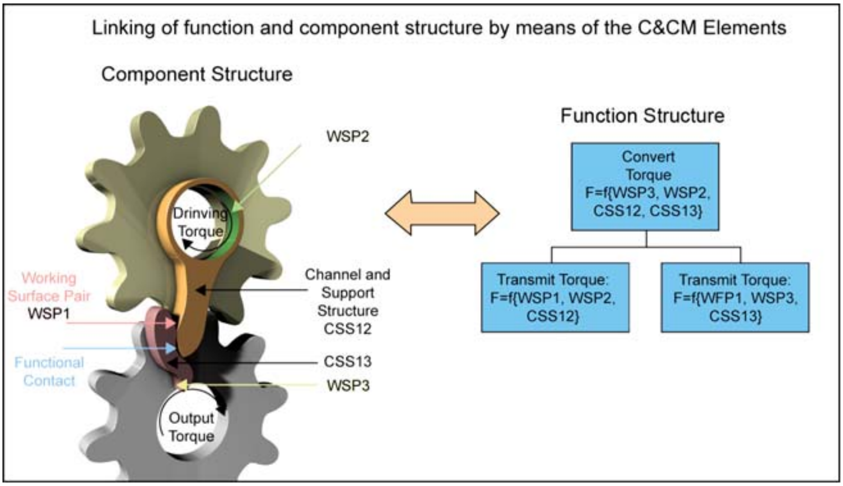

Fig. 1: Linking of function and form by means of C&CM elements

Their mental model building process is based on their experience. However, experience also may attract them to limit the search for solution in their mental field of experience and thus may exclude a better solution. Breaking fixation requires developing mental representations of what design should do and depart from physical embodiment [6]. In the core of the

C&CM there is a systematic function-component mapping that locates the functions on the components and thus makes functions visible (Figure 1). It provides a product model by means of Working Surface Pairs (WSP) and Channel and Support Structures (CSS) which are clearly defined on the abstract level of functions as well as on the concrete level of components.

The key idea of this approach is that a function of any technical system can only be fulfilled through interaction with adjacent systems in terms of action = reaction (Basic Hypothesis I).

Thus, an effect can only be obtained if a Working Surface (WS) is in contact with another WS and thereby creates a WSP. If this idea is systematized it becomes clear that a technical function requires a further WSP and a structure (CSS) that connects both WSP (Basic Hypothesis II). A technical function is defined in terms of the input-output relation of energy, material and information [12]. A whole system is completely describable through a structure of WSP and CSS (Basic Hypothesis III) [10, 2]. The functions are determined by the properties of the WSP and CSS.

2.2 Example

The gear unit shown in Figure 1 is meant to fulfill the principal function "transform torque". The system boundary is defined in the WSP 2 and 3 where torque (energy) enters and leaves the system. The structure between these two WSP (WSP1 and CSS12 and CSS 13) can be comprehended as the CSS of the gear unit. Two sub functions "transmit torque" (there can be further), which are each fulfilled through two WSP and a connecting CSS and are located on the single parts of the gearwheels and contribute to the principal function. If e.g. the WSP2 that represents the drive is not established because the interference fit assembly is wrongly dimensioned the function "convert torque" cannot be fulfilled. A system always needs interaction with its environment. By means of this systematic, the flows of energy, material and information that characterize the function of any technical system can be visualized on the physical embodiment through the allocation of the Working Surfaces (WS) as concrete tangible elements.

2.3 Proposed Procedure

The procedure follows the SPALTEN process like described in [1]. "SPALTEN" is the German acronym for the single process steps: S - situation analysis, P - problem containment, A - finding alternative solutions, L - selection of solutions, T - analyzing the consequences, E - deciding & implementing and N - recapitulation & learning. Here we run through the phases of the process of product analysis (Figure 2).

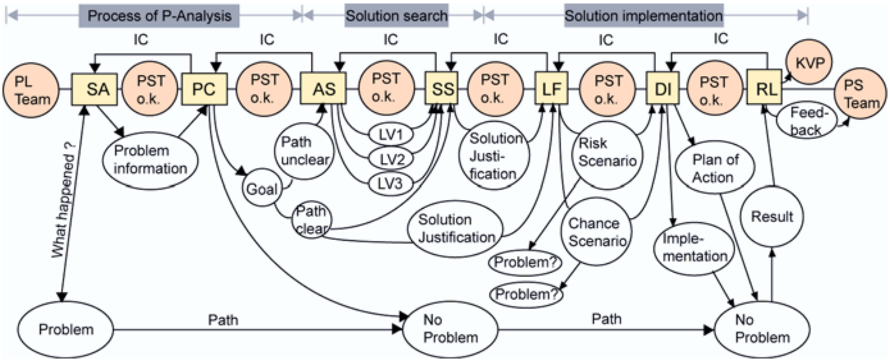

Fig. 2: SPALTEN Problem Solving Process

Structure of Functions on Shapes

In the core of this proposed procedure is the C&CM product model preparation that serves the situation analysis and the problem containment. The target is to generate a full understanding of the situation and therewith reveal all knowledge the designer collected during the original product development. The C&CM product model is used to show all relations between the elements within a product.

Any product consists of functional elements that are implemented on physical building blocks [15]. The kind of arrangement of these elements determines the product architecture. For a systematic improvement, these relations must be revealed in order to make them accessible for examination and handling. The model preparation process is executed as follows: We start by naming the main function. Then the WSP which define the input and output location of energy, material and information are located (WSP 2 and WSP 3 in Figure 1)

The next step leads to the sub function on the first lower level in a function hierarchy (Figure 1 right). We name these function and locate them on the parts in hand. The procedure is a kind of zigzagging between the function structure and the design parameters like proposed by Suh [13]. This makes sure that the analysis is developed on a high level of abstraction.

The further steps are accomplished starting from the physical description of the product: As it is very difficult to name the functions on the lower levels in function hierarchy we switch the starting point. We locate a WSP where an effect happens. We systematically go through the geometric features, identify the WSP and CSS and then name the function for which the elements are responsible.

Another difficulty that is opposed to this procedure is to name all functions that "happen" in a product. This includes unwanted function like vibrations or magnetic field effects. Thus, a classification of functions is carried out. In a first step we determined intended, unintended and supporting functions.

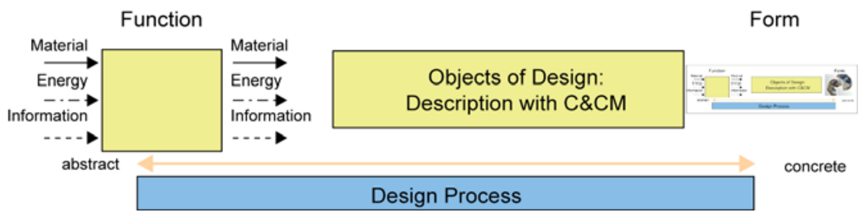

Fig. 3: Model elicitation can start from abstract or concrete

The procedure demands to ask from different points of view; from different levels of abstraction (Figure 3). However, a strict sequence of questions changing systematically between functional view and componential view is not suggested. In fact, we propose a free way of changing the point of questions. That is also supported by recent research results on design methodology. An opportunistic-associative procedure that allows the grabbing of sudden opportunities is often more effective than the deductive sequential procedure when solving problems [4]. For the designer it is important to know how to switch when this is required.

Examination of Elements

In the problem containment step the core of the problem is revealed. For a proper fulfillment of each function, it is vital that each of the WSP and CSS is implemented correctly. From the basics of the C&CM in [10, 2] we know that if a system breaks down or does not function properly one of the elements WSP or CSS does not exist the intended way. This means that the structure elicited in the product model needs to be proven in three ways.

1. Is any WSP and CSS build up correctly?
2. Is any WSP connected correctly trough a CSS to at least one other WSP?
3. Is there an interfering function that is connected with the intended function?

Thus, function failure can stem from the functional elements, the WSP or CSS; from the incorrect implementation of an intended function, the incorrect coaction of two WSP and a connecting CSS; and from the coaction of wanted and unwanted functions, i.e. the system behaviour.

3 Applying the C&CM Method

The developed procedure was applied in an industry project concerning the breakdown of friction bearings in engine support systems:

After an electric motor is assembled into an aluminum casing (Figure 4) unacceptable high failure rates occur. The failure crops up by a blocking of the shaft of the engine. The task was to find out what caused the breakdown of the bearings and to propose solutions for the improvement of the system with a strict requirement to change nearly no component.

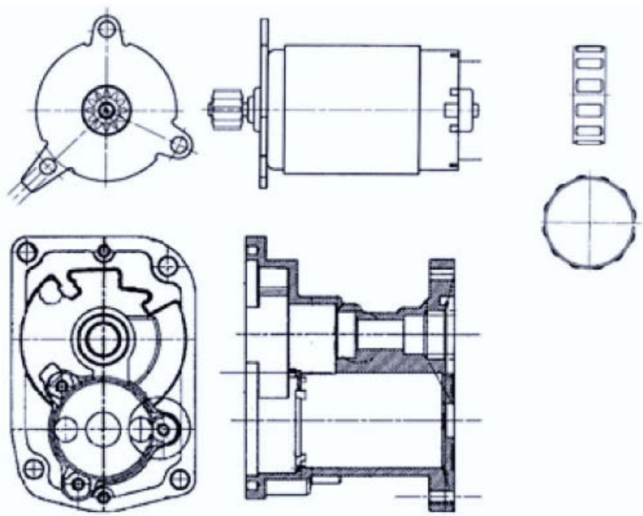

Fig. 4: Assembly of an engine support drive train

With the clearance of the boundary conditions situation analyses began. The main function was named. The system boundary was defined by location of the accordant WSP. Sub functions were named and the accordant WSP and CSS determined. By means of the C&CM it could be retraced which feature was designed for what purpose. E.g., normally the motor is only fixed at the welded plate on the gearwheel side (Figure 4). Due to the lack of stiffness, the rear side plug was used to mount the motor to the casing.

The effect of the failure was already named. The unwanted function is “blocking of the motor shaft” Now it had to be determined where this unwanted function places its WSP and CSS . The rear end of the shaft is pivoted in brass friction bushing. The blocking is caused by a deformation of the bearing itself. The assembly of the distance ring between motor and casing system causes a huge deformation in the range of the bearing seat. This deformation is caused because the function of the tolerance ring is not determined correctly (WSP 4 was placed wrongly during assembly). The failure could be detected because prints on the rear plug of the motor casing indicated that the WSP 3 (Figure 5) between motor casing and the inner side of distance ring was malformed during assembly. This resulted in a displacement of the WSP 2, WSP 1, CSS 12 and CSS 23, which are responsible for the bearing of the shaft (see Figure 5). The force transmitted was equal but the WSP 1 and WSP2 became smaller, CSS 12 and CSS 23 were deformed and disarranged the WSP 1 and WSP 2. The shaft blocked due to too high surface pressure in WSP 1.

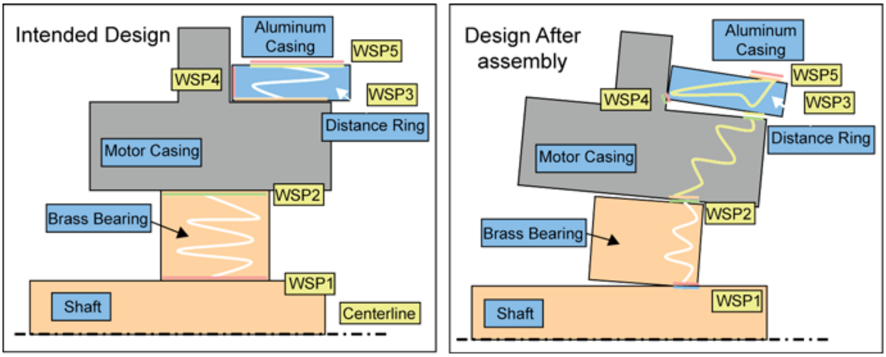

Fig. 5: The intended design and the failure design

4 Conclusion

The problem was handled successfully. The project partner out of the automotive industry was fully satisfied. It is certain that the benefit of a method is difficult to measure [7]. Also in this case it cannot be proven that the use of the C&CM can save money and minutes. Nevertheless, the methodological procedure in problem solving provides a neutral non-prefixated view on the product. And that is also the reason why an enterprise consults an institution like the IPEK. The function-oriented view, which focuses on what design should do apparently is attractive if development processes stumble in their usual ways. This supports our effort to advance the C&CM method in order to make it better applicable and to provide more engineers with the C&CM systematic.

This facet out of the research on the C&CM represents first steps of the development of a full C&CM method, which will give guidance in the preparation and use of the C&CM. The thoroughly formulated and documented basic definitions of the C&CM will be supplemented by a set of rules that are empirically gained out of the experiences, which numerous users of the C&CM make. In contrast to the basic definitions of the model, the on experience based guidance of using the C&CM is not yet formulated precisely enough. More case studies, which connect research and industry application, will contribute to a further improvement and acceptance of the method.

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The STEP Standards in Semantic Web – A Way to Integrate the Product Development Chain

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Abstract
Nowadays, the production enterprise may become a network of independent companies which share experiences, knowledge and capacities. However, to transform this network into a competitive advantage requires that information be exchanged efficiently. As project and component production are elaborated increasingly by a network of suppliers and as the process becomes faster to answer consumers' demands, the integration problem extends beyond the limits of the system and company. A new approach to this problem is the Semantic Web, an emerging area of research that purposes to guarantee interaction among information systems, to permit a variety of complex applications through the characteristics of semantic descriptions of web resources (data and services).

Keywords
STEP Standards, Semantic Web, Product Development Process, Data exchange

1 Product Development Chain

The product development chain starts with an idea that came from a need or an inspiration for appropriate methods to find solutions. A model is constructed from this idea and its objective is to start a process which will end with the material execution of the product.

In the process of producing a mechanical product through machining, the development cycle is well established and is followed by computer aided systems.

The digital integration of the phases of the product development chain is one of the objectives of the modeling systems. To achieve this objective it is necessary to permit that the specialist in charge of any development phase be focused on the information that is relevant to this phase, without losing the overall view of development [1].

The adoption of a friendly system, without restrictions to data exchange among different systems, will allow new levels of interaction in product development with reduced need for modifications [2, 3], since the product data do not need to be mapped or translated.

In a heterogeneous scenario the initiative of the ISO 10303 or STEP (Standard for the Exchange of Product model data) international standard has provided a neutral means for the exchange of data about the product model [4]. However, it can be argued that the use of standards per se cannot solve the problem of integrating the product development chain.

2 Conception of the Product Data

Due to the fact that each activity of the product cycle may generate a component of the product data model independently and with no concern for the subsequent phase and its integration, the product data model may be characterized by a heterogeneous database system [5].

The discrepancies may occur at any level of abstraction (data, schemas or models). Heterogeneity may be directly checked in the data representation or just be an interpretation matter. The integration of different database may diminish the capacity of each component to manage its own data without general interference by the heterogeneous database system [5].

The integration of heterogeneous data requires conflict resolution of heterogeneity and the transformation of data sources into an integrated whole [6].

Among the ideas developed for the integration of heterogeneous data, the one that offers the widest range is the establishment of standards for data models and syntax, specifically the STEP standards which have achieved great success. The use of semi-structured data gives versatility to data representation, allowing data transformation and mapping of irregular structures.

One of the greatest difficulties in the integration of heterogeneous data is the semantic loss of components. As typical data modeling takes semantics with it, information may be lost in the conversion of data from a data model into semi-structured data. This problem may be managed by the maintenance of a metadata set associated to converted semi-structured data. Therefore the solution to semantic conflicts is in the normalization of meanings, concepts, terminology and in the structuring of the data source. This has been achieved by STEP standards, which enriches the metadata to support the investigation of the semantic adjustment among data values of different data sets.

3 STEP Standards

The ISO meeting in Frankfurt, Germany in 1989 marked the implementation of the STEP standards. The present structure of the STEP standards is a consequence of a great number of contributions.

With the aim of achieving the proposed objectives, the STEP standards were developed in a modular structure to guarantee necessary flexibility. The various modules are documented in separate parts in the ISO 10303 International Standard [7]. The group of product data definitions that can be supported by STEP is subdivided into a number of independent modules with clearly defined interfaces. To exchange data among CAD systems, the STEP standards provide an implementation method defined in Part 21 as a physical file in sequential text format. In the development phase, Part 28 defines the physical file in XML (eXtensible Markup Language).

Since it is not possible to have all the possible applications in a single data group, or offer a concrete context for the data, the STEP standards use Application Protocols, which describe the utilization of data exchange for a particular application, thus reducing the scope of each protocol to a business area. Although the standards are a key factor to data integration success, they are not by themselves the guarantee to this success [1].

4 Semantic Web

The Semantic Web is an emerging research area, whose objective is to guarantee integration among information systems and to permit a variety of complex applications through semantic descriptions of Web resources (data and services). It is an infra-structure in which different applications may be developed. Another proposal is to increase the present Web with the formalization of knowledge and data that different humans and/or computers may share and process [8].

The key requirement to Semantic Web is interoperability. Data and metadata must correspond to consensual formats and concepts to enable sharing and processing. Figure 1 shows the layers of standards and technologies of Semantic Web.

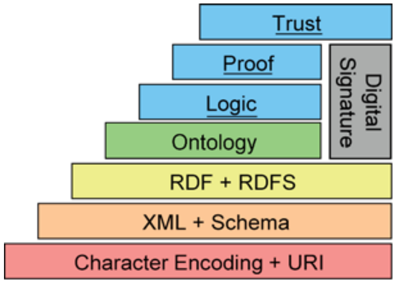

Fig. 1: Infrastructure of the Semantic Web

The bottom layer, Character Encoding and URI, establishes an international standard – UNICODE – for the set of characters and a meaning for a single identification of resources in the Semantic Web.

The XML layer, which includes namespaces and schema definitions, is constituted by a standard syntax, which gives the basis for data model description in such a way that the exchange of information and schemas may become possible.

On the third layer, the RDF (Resource Description Framework) permits statements that associate resources with property while the RDFS (RDF Schema) enables the definition of vocabularies that may refer to the URIs in which they are published. These vocabularies may be used to associate types to resources and properties.

The ontology layer enriches the vocabulary and permits its evolution, extending the repertory of concepts and semantic relations among words.

The upper layers – Logic, Proofs and Trust – are in development.

5 Correlations between STEP and Semantic Web

The proposed solutions to data integration come from common pretexts and are, therefore, similar. In a specific application, the STEP standards were developed as metadata standards [6, 9], which fit perfectly into the Semantic Web proposals. Since a wider amplitude is their initial objective, they also present a wider solution. In the next part, the existing correlations between the two solutions will be presented.

5.1 First Layer: Unicode and URI

The use of an international standard for the characters used in the whole Semantic Web is the minimum requirement for subsequent phases to be able to work with the same data.

```
<?xml version="1.0"?>
<MechanicalPart xmlns =
http://www.unimep.br/feau/scpm/MechPart.xml Name="Torre"
PartNumber=10001>
      <Machining Feature>
            <Slot>
                  <LocationX> 0.000 </LocationX >
                  <LocationY> 15.000 </LocationX >
                  <LocationZ> 100.000 </LocationX >
                  <Width> 10.000 </Width>
                  <Depth> 15.000 </Depth>
            </Slot>
...
      </Machining Feature>
</MechanicalPart>
```

Fig. 2: XML Document for a mechanical product

In this aspect the STEP standards do not assign UNICODE explicitly, but implicitly the whole standard is structured according to this international standard, though just a part of it is used.

Figure 2 presents a document in XML, using UNICODE characters to describe a mechanical product. The XML syntax not only permits that this file is exhibited in any web browser, but also accumulates information about the product in an extensible way.

5.2 Second Layer: XML and XML Schema – AAM

The schema languages for XML are DTD (Document Type Declaration) and XML Schema. Schema specifications may be stored together with data in XML or in separate documents, which can be referenced by several XML documents. The DTD is, itself, a specification of XML, defining the structure of the XML document by the use of a list of element type declarations. These declarations define types of atomic components in XML and the nested structure of compounded elements.

The XML Schemas offer a syntax based on XML to describe the structure and the content links of an XML document [6]. Figure 3 presents an XML Schema for a document of a mechanical part with the following structure:

the first line has the description of the area named for the vocabulary of the XML schema, the second line shows that a document, in conformity with the presented schema, must have an element named “Mechanical Part” of the “MechPartType”. This type includes nested “AggregValues” elements to store the essential information of each one of the manufacturing features.

```
<xsd:schema xmlns:xsd=”http://www.w3.org/2001/XMLSchema”>
   <xsd:element name=”MechanicalPart” type=”MechPartType”/>
   <xsd:element name=”Slot” type=”MachiningFeature”/>
   <xsd:element name=”Hole” type=”MachiningFeature”/>
   ...
   <xsd:sequence>
   <xsd:complexType name=”MachiningFeature”>
       <xsd:sequence>
           <xsd:element name=”LocationX” type=”decimal”/>
           <xsd:element name=”LocationY” type=”decimal”/>
           <xsd:element name=”LocationZ” type=”decimal”/>
   </xsd:sequence>
   </xsd:complexType>
</xsd:schema>
```

Fig. 3: XML Schema for a mechanical part

Due to the lack of semantic information, the schema description, by itself, is not enough to ensure the correct interpretation of data in XML or to permit their integration. For example, there is no indication of the measurement units and of the co-ordinate system used. This example shows the need for associating the conceptual meaning with data in XML and its markings. The use of schema and standardized metadata, once well documented and with common meanings, may reduce this problem [10].

The AAM (Application Activity Model) is one of the three main elements of a STEP application protocol [7] that describes the business process that supports the information model. Thus, it has the same objective as the XML layer and XML Schema. Since it is described in a specific language of the norm, the EXPRESS/ESPRESS-G, the characteristics of object orientation are present in both languages and there are no barriers to a direct translation [9].

5.3 Third Layer: RDF and RDFS-ARM

The Resource Description Framework – RDF – is the main format for computer processing of metadata in Semantic Web. RDF is based on the representation of formal knowledge such as tables and logic descriptions. The basic building of a RDF model is an assertion, a triple in the form of a ‘subject

- predicate - object", where the subject refers to any resource (anything that may be described with the URI), the predicate is a property of this resource, and the object is the value of this property. The object can be a literal (e.g. a sentence) or any other resource.

RDFS (RDF Schema) is an extension of RDF with classes of resources, values and properties. An RDFS specification defines a structure of classes, properties and sub-classes for a particular domain or application, similar to a category diagram of an object oriented model [10].

Figure 4 shows the use of RDF and RDFS for the description of Web resources. At the upper part, two different schemas, describe resources to work the data of a model. The RDF schema on the left describes the resources to work with the geometric model, for example, visualization, while the system on the right collects the product data for the process and carries out process planning services.

Each specified resource in RDF at the bottom of figure 4 is an instance of some class (e.g. another resource of the same type) of another RDF schema in the upper part. For example, the slot is an instance of a prism in the schema on the left and an instance in the machining operation on the right. Definitions involving instances of resources must be compatible with definitions of the RDFS level.

Besides providing different views for the same resources, RDF/RDFS also help to define unified views of heterogeneous resources. For example, a slot has a geometric interest in modeling, while for the process this same entity defines the type of tool and its path. The tolerance characteristics have different consequences in machining and measurement. The different computer-aided systems also define the same entities differently. For a CAD system, a slot is a prism defined by its borders; for a CAM system the same slot is defined by the way the tool performs to machine it. Another major problem is the different ways of describing an entity among different systems. Various levels of RDF/RDFS descriptions may provide the solution to these conflicts. The RDF/RDFS standardizations are important in the following aspects of Semantic Web:

- State the relations involving resources and resource description;
- Allow different views of the same resources, adjusted to their different fields of action or applications;
- Build unified views for collections of heterogeneous resources;
- Describe knowledge using vocabulary of concepts and the semantic relations among these concepts.

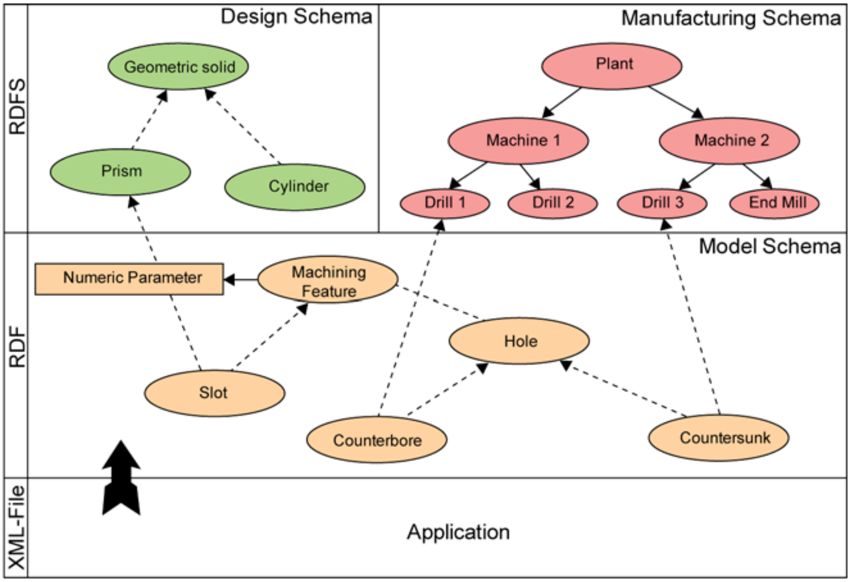

Fig. 4: RDF and RDFS for a mechanical part

In comparison with the STEP standards, the ARM (Application Reference Model) specifies the information requirements within the scope of a specific application protocol to reduce the domain to an area of knowledge.

As well as for the previous layer, there is no difficulty in translating the Reference Model of EXPRESS/EXPRESS-G to XML.

5.4 Fourth Layer – Ontology – AIM

Ontology is the science that studies the concepts that enable us to know and determine the consistence of things. A consequence of ontology is the set of concepts that, when shared, establish knowledge about a delimited domain. An ontology organizes definitions and inter-relations involving sets of concepts (e.g. entities, attributes, processes). Ontology is able to capture the meaning of class and instances in a speech universe by the arrangement of symbols (e.g. words, expressions, symbols) according to their semantic relations [11].

Defining ontology for shared knowledge allows a precise definition of any consultation and the correct answer, even in open environments. Ontologies also help in data integration, particularly in the investigation of correspondence among data elements that come from heterogeneous sources [12].

The basis for the implementation of the STEP standards within an application protocol and, therefore, in a specific domain is the Interpreted Model, which is based on STEP integrated resources. This mode is described in IDEF0, which could result in another difficulty with translating to the ontological languages expected by the Semantic Web, but since the concepts are the same, this obstacle is easily overcome [13].

6 Conclusions

The Semantic Web is a vision for the future of the web in which information is given explicitly, facilitating the automatic processing and integration of the information available in the web. The Semantic Web will be built with XML ability to define tag schemas and RDF flexibility for data representation.

The Semantic Web requires a layer of ontology on RDF, which can describe the meaning of the terminology used in Web documents formally. In the hope that computers execute useful and meaningful tasks with web documents, the language to support the RDF schema is XML, exactly as it is previewed by the STEP standards and Semantic Web.

To transform the STEP physical text format file to XML is the first and most important step to the integration of the whole product development cycle. Enlarging the product integration to the ERP (Enterprise Resource Planning) and CRM (Customer Relationship Management) tools is a task for the future.

Just using XML without any other implementation enables several processes: the data product model may be viewed in a simple browser, the additional attributes are not lost in the model and the sequence of model construction may be maintained.

7 Acknowledgments

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Configuration instead of New Design using Reference Product Structures

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Abstract
A variant management has the goal to offer as many product variants as possible to the customer but keep the internal variety in the company as low as possible at the same time. Inevitable creation of new parts or subassemblies has to be controlled in a standardized process of variant creation. To provide sustainability the new product data has to be integrated into the existing product data model in order to support the creation of a new product variant. This paper discusses the management of product data using reference product structures as well as reference products, and the support of a product data management system (PDMS) within the context of product lifecycle management (PLM) strategy.

Keywords
Variant Management, Product Data Model, Reference Product Structure, Product Lifecycle Management (PLM)

1 Introduction

In order to remain competitive on the market, besides offering good products, companies with high product variety must also optimize the creation process of its products. As customers expect individual products, a company must be able to handle the internal variety resulting from highly customized products. Due to market pressure and low time to market a company, especially a design engineer, should be able to create a product variant, which fulfills customer requirement, using as less effort as possible not only concerning of the design process but also paying heed to neighboring processes as manufacturing and assembly.

This problem grows with the product complexity and the number of engineering designers involved as well as the complexity in the organization, which induces department boundaries. An engineering designer is not able to find an already existing data/information, which is relevant for the new order/requirement in a proper time. Surely there are many rules of standardization already defined within the companies internal design manual. But due to time consuming search processes, the engineering designer often doesn't consider this standardization. It is much easier for him to create a new component or new assembly rather than using any existing ones. On this account the internal complexity will rise rapidly.

This problem should be handled at least by accounting the two aspects product data and process. Both are interrelated, affect each other and will be considered in the frame of a PDMS application as product data model and process model [1]. The third aspect in this context, the role model as a transformation of the organization within the PDMS, will not be discussed in this paper. This paper describes a management of product data using a reference product and its structure, which can be utilized as a storage platform for parts and assemblies within a certain product family. The product variant to be delivered to the customer is a derivation of the reference product. The engineering designer will be supported and encouraged to configure rather than to design. The reference product structure supports the engineering designer to find the right data for fulfilling the new requirements and can be used as a basis for collecting the knowledge in a knowledge pool. Furthermore, the necessary prerequisites for implementing a reference product structure will be discussed. The definition of the processes within variant creation and the definition of the data structure in the product data model are also covered by this paper.

2 Current Situation

To minimize the work effort to derive a product variant a company has to plan their variants right from the beginning of initial product development. The company must therefore perform an extensive market analysis to retrieve basic information in order to set up the products. The product variety should be planed as detailed as possible before market launch.

In practice a lot of companies do not sufficiently plan their product variety within their portfolio. A new product generation is developed based on a certain scenario of requirements. A product variant will be produced through modification or adjustment on another existing product (Fig. 1).

Due to the requested flexibility of fulfilling customer's requirements, lack of communication between engineering designers and marketing, regarding customer's wishes as well as shortened development time, a new product variant will be "tinkered" from an existing product variant, which seems to fulfill the requirements with only minor modification. All product data, including the newly created product variant will be stored in a product data repository without any sufficient reference to each other.

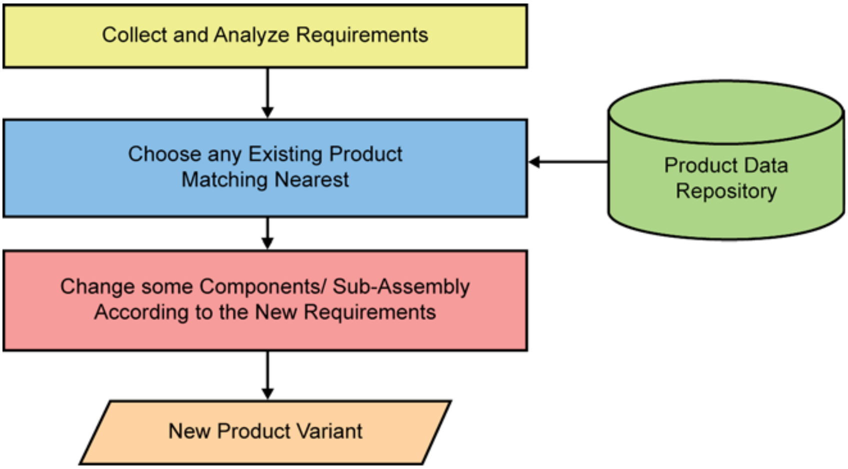

Fig. 1: Common variant creation process

This proceeding induces a huge number of variants of parts and assemblies within a very short time, because there are lots of special customer solutions to be developed (Fig. 2). The interconnections and references of parts and assemblies become unclear and forgotten. The reuse of existing parts and assemblies is aggravated or worse prevented.

Within a company with high product variety it is very difficult for a single engineering designer to gain an overview of all existing parts and subassemblies. Many companies will actually propose a standard regulation that the engineering designer is only allowed to use standardized parts and assemblies. In practice, it is difficult to comply to such a regulation, because the engineering designer is bound to the realization of the customer's requirements. The problem is aggravated due to the boundary in between sub departments within an engineering department. The experience and information remains only within a sub department. The exchange of information spanning departments is merely minimal.

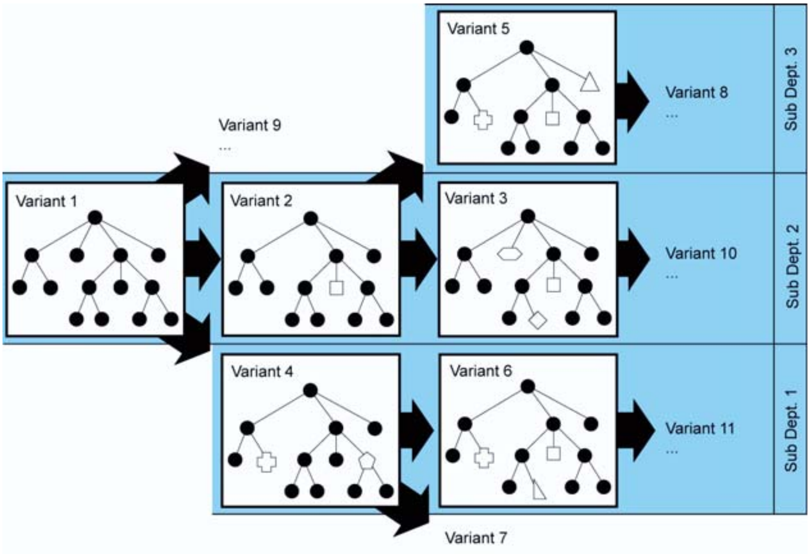

Fig. 2: Random generation of new product variants from any existing variant

Furthermore the activity of finding an existing solution usually consumes too much time because most companies lack supportive tools regarding the context of knowledge management. The product data is allocated in many different data storages with data redundancy and without references to each other. Most companies tend to have no product data model at all.

Within a regular interval, companies run a variety cleanup. Although this measure is necessary, it doesn't solve the initial problem, i.e. the creation process of new product variants itself.

This results in a situation, that most engineering designers spend a lot of time for the coordination of activities such as marketing coordination, clarifying requirements questions, conducting data retrieval and many more. These activities provide no added value and should be avoided as much as possible.

Out of the current situation, the following points have to be considered:

- The creation process of the product variant should be arranged in such a way, that usage of existing parts/subassemblies is with a high priority is secured. Furthermore the process has to take the sustainability of the data reference into consideration.
- The product data model has to be defined and used consequently in order to enable easy information retrieval.
- An appropriate IT support with accompanying tools is essential in order to be able to work efficiently.

3 Existing Approaches

A variant is regarded as an alternative solution, which differentiates from another solution in at least one qualitative or quantitative parameter value [2]. There are three aspects of reasons for variant creation [3]:

- external (technology development, social/political alteration)
- market
- internal (cost, deficit of method/organization).

The product structure is a model, which describes the determined interrelation between parts and subassemblies of the product in entirety concerning certain points of view (e.g. manufacturing, assembly, function, disposition, calculation) [4]. The product structure describes the real physical interrelation of products and expresses the interconnection of subassemblies and parts or more complex technical systems [5]. This product structure is documented by the bills of materials and sets of drawings or similar models. The bills of materials usually mark the central sorting criterion within a company, which usually inhibits a manufacturing or dispositional point of view.

To optimize the design process, one prerequisite is to reuse effort spent in the past as often as possible for a new product variant. This can be achieved by the definition and determination of standards for parts/subassemblies and processes. This demands for rationalizing the working process. The main approach is to substitute mental-effort by routine-work [4].

There are several approaches of standardization in order to minimize work effort such as size ranges, modular product design, modular product design, platform and feature technology [3, 5].

Schuh (1989) introduced a representation of product structures complementing high variety in a so called variant tree, in which the number of components on every assembly level is pointed up [6]. The method was developed considering the circumstances of the automobile industry.

Bongulielmi et. al (2005) use a so called K-&V-matrix method to allow a structured representation of the variability of products and product properties independent from the complexity of the related machine or plant [7]. Therefore the meaningful existence of a product variant is analyzed against the future requirements of the markets.

There are many approaches of variant management in literature. The companies acknowledge the problem and are aware of the described existing approaches. But lots of companies with high product variety deter to perform the approaches, because they largely demand comprehensive preparation and penetrative changes regarding system architecture, data migration of running system, loss of flexibility or additional employee training as examples. In many cases the approach is also accompanied with high financial effort as a result of hiring a consultant firm.

Thus a practical approach, which can be implemented right away little by little and performed by the company itself is to be developed. This approach can be used as a preparation for the implementation of another approach in the next product generation. The approach consists of configuration of the product data model using a reference product structure to support the process of variant creation and will be introduced in the next chapter.

4 Reference Product Structure

The reference product structure can be derived using similarity analysis of existing products. The ideal product portfolio evolves from just one reference structure, so this possibility has also to be taken into consideration. Because the ideal rarely occurs in practice, products with high relative percentage of same components will be grouped within a certain product family. It is therefore appropriate to define one reference product structure for a certain product family.

For the similarity analysis, several typical products of the companies' product portfolio has to be taken into consideration. The product structures of these products are to be analyzed closely. Identical or similar parts or subassemblies are put on the same position within the structure. Hereby it will be differentiated between parts and subassemblies, which are:

- Matching exactly. This will be defined as standards within the company or at least within the product family.
- Standard options and/or standard adjustment.
- Customer specific solutions.

The result is a product structure, which contains all structural positions of existing parts and subassemblies. This product structure will be adopted as a reference product structure.

Within a reference product structure, some reference products can be defined. A reference product is a reference product structure filled in with items and can be determined on the basis of the reference product structure and product families. The grouping of products in product families depends strongly from the use case. Therefore it could be necessary to define several reference products within a product family. These reference products have the same structure but differ in their functionalities and/or size. Since engineering designers tend to think in product functionalities, they can find the reference product which suits the new requirements quickly.

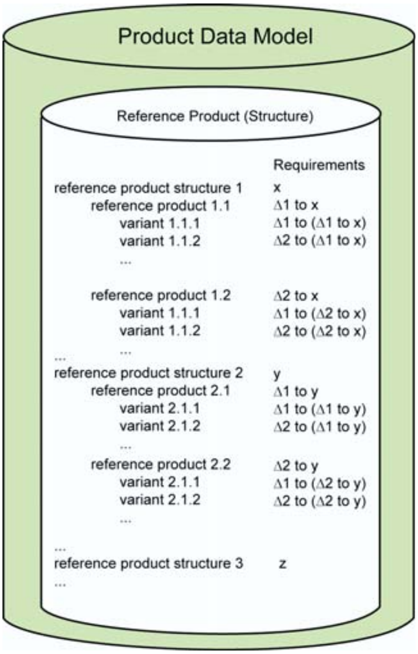

Fig. 3: Reference products within a product data model

All variants derive from a certain reference product. Ideally, all parts or subassemblies fulfilling the same functions are stored at the same structural position within the reference product.

The interrelation between product variant, reference product and its structure will be determined by the description of requirements. A certain reference product structure represents certain product requirements. The requirements of a reference product is described, using the difference to the requirements of its reference product structure. The same thing will be applied for the product variants, whose requirements are described as a difference to its reference product (see Fig. 3).

5 Variant Creation Process Using Reference Products

In order to use the reference product and its structure, a standard process of variant creation should be defined. It covers the responsibilities for changing data. A modification of the structure has to be avoided at all cost. A demand of change for the initial structure must be proven by an experienced employee, who has the necessary competence. The indispensable adjustment of parts or assemblies must be examined not only under the aspect of design, but has to take manufacturing and assembly of the product into consideration as well. Therefore it is important to name a person in charge for every position within the reference product structure, which has to approve the demand of all modification.

Furthermore, since parts and subassemblies are stored within the reference product, a product variant can be easily derived from the reference product by a configuration (Fig. 4).

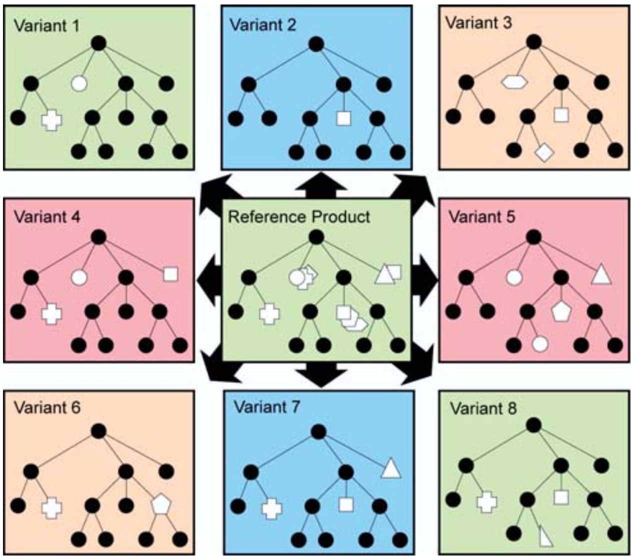

Fig. 4: Product variants derived from a reference product

6 PDMS Application

The entire management of the process and product data will be consolidated by a company repository, which contains all process and data with according references (Fig. 5). This company repository is an key element to support a PLM-strategy.

PLM is a knowledge based company strategy for all processes and their methods in regard to product development from the product idea up to recycling [1]. A PLM strategy aims for supporting the integrated management of the products throughout their overall life cycle. A central component of an IT-environment supportive for PLM is a logical integrated and cross-linked product data model [8]. The implementation of this strategy requires the usage of a PDMS.

The presented approach can be efficiently integrated in the introduction of PDMS, if not already performed yet. During a PDMS introduction the product data and the processes has to be adapted anyway [9]. It could be necessary to redefine processes and implement them by workflows.

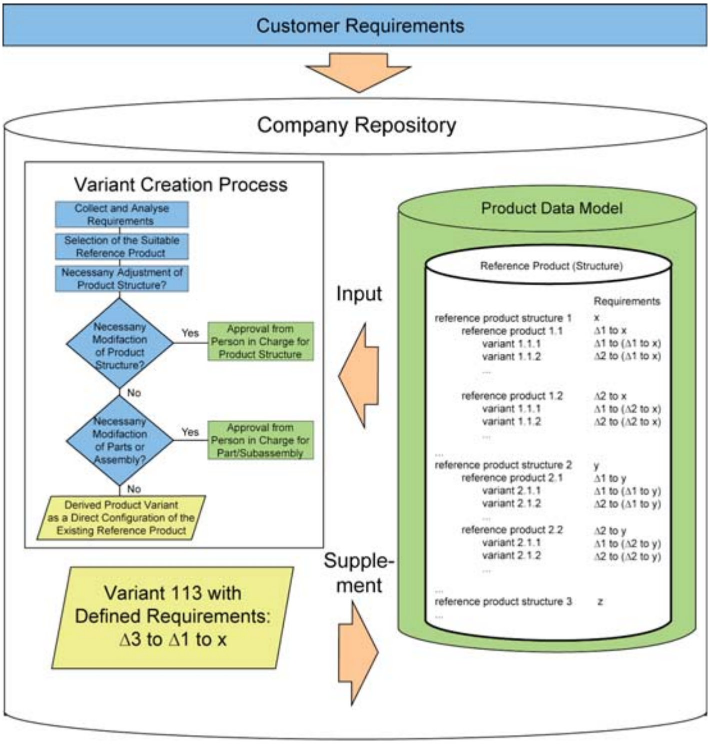

Fig. 5: The variant creation process and product data model as part of company repository

The creation of a product variants in a PDMS could be done by configuration rules adverting a reference product [10]. The meta data of the parts/assembly includes the description of the requirements.

7 Conclusion

This paper introduces an approach to implement reference product structure supporting the variant creation process within a company with high product variance. A product data model containing the product data with its references between each other and a variant creation process will be integrated by the means of a company repository, which is the basis for the implementation within a PDMS. Engineering designers should be kept off from avoidable coordination activities to better concentrate on working to find innovative solutions for the products.

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Implications of Complexity in Early Stages of Innovation Processes for the Definition of Heuristic Engineering Methods

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Abstract
Heuristic engineering methods can provide essential support of management of informational complexity in early stages of innovation processes. This paper applies principles from system and model theory to the development of a meta-method, i.e. a method to support the definition of heuristic engineering methods. The resulting framework facilitates discursive procedure in method development and operative engineering activities respectively, and provides increased understanding of fundamental method mechanisms with regard to informational complexity.

Keywords
Complexity management, method development, meta-method

1 Introduction

Continual shortening of innovation processes and innovation cycles characterise the current competitive environment. At the same time, customer expectations rise concerning functionality and quality of products, and their costs. Thus, customer requirements and innovation necessity result in conflicting innovation process targets regarding reduction of costs, reduction of time-to-market, and increase of quality. This leads to according change of process requirements. In addition to further time or cost reduction, e.g. increasing life cycle orientation, changes in legal regulations or linking of products and services may cause new requirements. Against this background, managing complexity has become an essential challenge for enterprises in the market. This challenge concerns all hierarchy levels of the collaborative value chains, and directly affects the employees, which are the key to the success of many of these processes.

2 Role of Methods in Complexity Management

2.1 Conceptual Foundation

The term *system* refers to entities, which are not to be considered merely sum of their parts, but require a holistic approach for reasons of interrelations between these parts. A system is defined as a set of elements and their relations. Inputs and outputs connect a system to its environment, from which a system boundary separates it [1]. Systems result from determination by observers. The term *element* demonstrates this, referring to entities not being further resolved within a specific chosen perspective [9]. System determination depends on the observer's frame of reference. For evolutionary reasons, it is often mapping in time and space. Therefore, observers often do not discriminate between systems and objects. However, a system is always a *model* made by an observer of an original, but not the original itself [6]. A model is a mapping of a natural or artificial original, which also can be a model. Its being based on originals is referred to as *mapping feature* of models. Other features of models are *reduction feature* (a model only reflects a relevant set of properties of the original) and *pragmatic feature* (a model is not unambiguously associated to an original per se, but fulfils its replacement function only for specific subjects, within specific time intervals, and for specific purposes) [13]. This concept of models is broad and includes every purposeful, material or immaterial abstraction of a material or immaterial original. However, system models in a stricter sense are mental interpretations, and as such can only be immaterial abstractions of material or immaterial originals.

Model theory is itself a model, and as such needs pragmatic justification [13]. This applies to system models as well. Practical application of system theory (Systems Engineering) is often justified by its providing effective means to handle *complexity* [1, 3]. Complexity in a narrower sense (i.n.s.) refers to a property of a system model, resulting from type and number of elements and relations each. Complexity in broader sense (i.b.s.) refers to a property of a situation, in which complexity i.n.s. and further complicating situational factors (such as dynamics, intransparency, ignorance, and false hypotheses) confront an agent. Complexity i.n.s. and i.b.s. is therefore subjective: It requires the existence of an observer, and depends on the purpose of system modelling and on knowledge and experience of the agent in the context of similar system models and situations [3, 6].

A *method* is a set of instructions, whose execution under given conditions sufficiently ensures achievement of an intended objective [9]. A *process* is an activity or set of interrelated or interacting activities using resources to transform inputs into outputs [8]. Methods as descriptions of recommended or intended activities therefore are process models, regardless their formulation and concretion. Since activities can be regarded as elements of processes, and inputs and outputs provide interfaces to other processes or the environment, processes can be interpreted as systems, and methods, being procedural process models, as well.

2.2 Complexity in Early Stages of Innovation Processes

Several factors cause complexity i.b.s. in early stages of innovation processes, i.e. product planning and development. Important reasons are functional *plurality* and product *individualization* required for competitive reasons. Requisite model and option diversity calls for measures like size ranges, modular products, or package systems, increasing complexity i.n.s. of technical products [4, 11]. Also related to the competitive environment is increasing *interdisciplinarity* of technical products. Mechatronics enables new functions and principle solutions at improved efficiency, and therefore can facilitate success in global competition. In return, close interrelation of components from different domains significantly increases complexity i.n.s. of technical products [5].

Complexity i.b.s. results from the nature of developmental activities and their environment. The goal of *developmental activities* is anticipation of technical products based on specific objectives, i.e. designing structures of i.n.s. complex systems to cause specific behaviour. Since behaviour does not unambiguously determine structure [7], developmental decisions include certain degrees of freedom. However, the impact of such decisions is difficult to assess in early stages of innovation processes [4]. The interconnectedness of the elements of the technical system in question (i.e. complexity i.n.s.) is responsible for this. Furthermore, engineering design objectives can be undetermined, generic, unclear, implicit and conflicting [3, 11]. In addition, the *developmental environment* is dynamic and opaque with respect to informational relations. Both design objectives and means to their achievement are therefore uncertain and changing [4, 5, 11].

This complexity i.n.s. and i.b.s. is essentially *informational complexity*, as it challenges engineers during problem solving, i.e. information converting activities [2, 3] (Fig. 1).

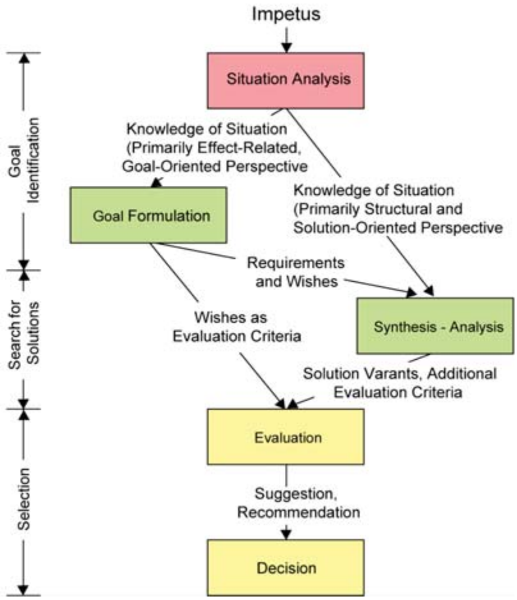

Fig. 1: Informational relations between problem solving steps [1]

2.3 Meta-methodical Requirements

Methods can substantially contribute to ensuring and increasing quality in processing of complex engineering design tasks, as they can effectively organize the entirety of supporting factors [1, 9]. Even though heuristic methods are by definition incomplete and cannot guarantee reaching their objectives, they are nonetheless essential for the organization of processing of complex tasks [9]. Thus, methodical support of the definition of heuristic engineering methods is essential to improve management of complexity in early stages of innovation processes. The term *meta-method* refers to such a method, whose intended objective is the definition of methods.

Methodical support is required to support the development of good solutions with sufficient reliability and acceptable effort [1]. This makes the ability to support the *definition of heuristic methods* with regard to the *management of complexity i.b.s.* of *engineering tasks in general* an essential meta-methodical requirement. Since method development for complex tasks is a complex task itself, management of complexity is a direct and indirect meta-methodical requirement (Fig. 2).

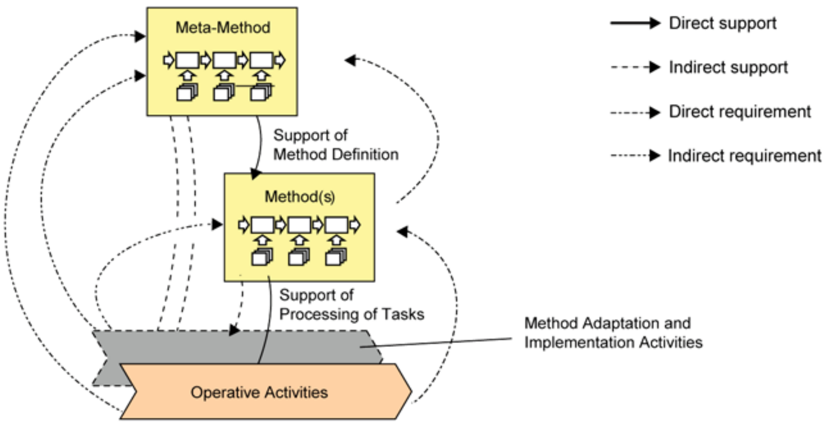

Fig. 2: Direct and indirect support and requirements

Application of abstract methods, i.e. implementation as processes, may concern process management in addition to individual engineers. For this reason, *operative and process support* is required of the meta-method. Heuristic methods should be suitable for implementation, even though not being process management methods per se.

Complexity often prevents problem awareness, which is necessary for intuitive problem solving [4]. Discursive procedure therefore is more appropriate for i.b.s. complex tasks. Consequently, *support of discursive procedure* is a direct and indirect meta-methodical requirement. Method development and operative procedures are required to be systematic and incremental. As discursive procedure increases method transparency, this also contributes to method acceptance and practicability.

A meta-method should be *suitable for top-down and bottom-up approaches* and for combinations thereof. Considering the necessity of discursive procedure, this requires support of incremental concretion, and abstraction and aggregation of procedural models. These approaches need to follow consistent criteria to support flexible application.

As system models, methods can be structured hierarchically. Using existing methods as sub-systems in method development can increase efficiency of method development. This requires support of *selection and at least qualitative evaluation of existing methods*.

3 Systemic Approach to Method Development

Methods are results of method development processes. Like product development, method development comprises designing of procedural structures of abstract system models, which cause desired behaviour when executed. From this systemic perspective, method development requires the definition of elements and relations of procedural process models. At the same time, method development is a process and a meta-method thus is a procedural process model as well. Consequently, and with respect to implicit self-applicability of the meta-method, *consistent structuring criteria* are required to structure both the meta-method and the resulting methods. As processes and methods are procedural, such structuring criteria need to comprise *operations and their objectives* (Fig. 3).

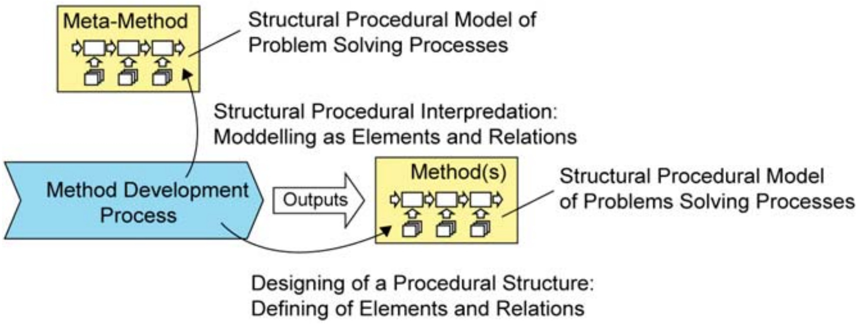

Fig. 3: Requirement of consistent structuring of methods and meta-method

Product development tasks are planning problems, which are self-referential in nature: On the one hand, comprehension and description of a problem at hand requires a notion of its solution. On the other hand, problem understanding is an essential part of the solution [12]. Likewise, method development is a circular structure of interdependent problem understanding and problem solution: Methods support activities, which are accessible in abstract manner only via descriptions. Clarification of method development tasks therefore requires a notion of the future process, i.e. a procedural process model. However, to develop such a model is the objective of method development. Because of this circularity, *abstraction from activity context* can facilitate method development.

System and model theoretic interpretation of method development enables identification of operations and objectives, which at the same time are suitable for use as structuring criteria and abstract from concrete application context. Interpretation of methods as both abstract system models and outputs of processes leads to identification of different levels of abstraction, and of the respective determining factors at these levels (Fig. 4).

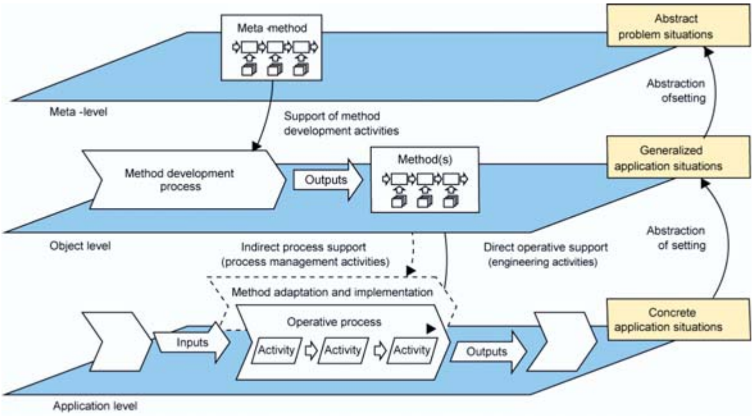

Fig. 4: Context of method development and application

Tasks of concrete application situations are processed at *application level*. Method development at *object level* focuses generalized application situations, since methods are supposed to be invariant for classes of tasks [9]. Both method development and operative processes are problem-solving processes. The determining factor for operative problem solving is concrete *information*, e.g. concrete requirements in product development. To provide operative support, methods need to consider *complexity-related properties* of the information processed at application level, e.g. dynamics or opaqueness of market information used to define product requirements.

Further abstraction from generalized application situations leads to *abstract problem situations*, at *meta-level*. These refer to specifics of information transformation barriers, suggesting *information conversion aspects* as determining factors at meta-level. Psychological, technological, and organizational aspects are relevant, since information conversion in problem solving depends on cognitive performances, on support by information and communication technology and on integration in existing process structures. These aspects focus cognitive processing, representation/modelling and communication of information, and thus are referred to as content, form, and fluency respectively. These information conversion aspects can serve as the *objective* dimension of the required abstract structuring criteria. Corresponding abstract information converting *operations* are analysis (determination of information properties), acquisition (active gathering of information), pre-/post-processing (changing of information properties, mainly form-related), and synthesis (definition of new information). Combinations of these operations and their objectives structure the method development process and at the same time provide generic building blocks for method development. With respect to method development, these operations focus on information conversion. During the subsequent method adaptation and implementation stage, their focus is on corporate resources, shifting from qualitative (capability) to quantitative aspects (capacity) (Fig. 5).

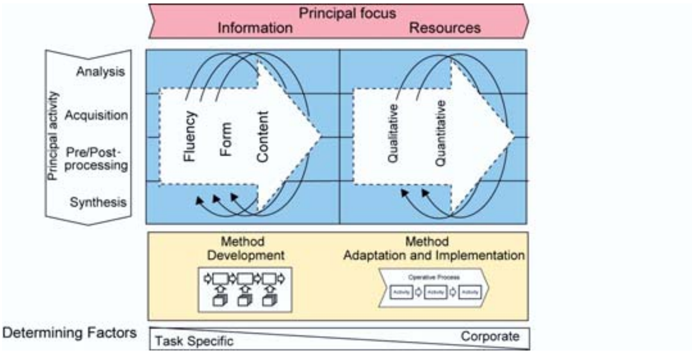

Fig. 5: Meta-methodical framework

Top-down application of this meta-methodical procedure starts with analysis of process boundaries and interfaces (given inputs and required outputs), determination of input properties essential for complexity i.b.s., and determination of output properties relevant for goal-oriented execution of subsequent processes. This analysis provides foundation for specification of further input acquisition and input pre-processing steps, which allows outlining synthesis activities and output pre-processing steps. The result is a *conceptual method schema*, i.e. a schematic sequence of abstract operations to transform informational inputs into outputs. Conceptual method schemata are independent from application context, and take into account causes of and measures to manage informational complexity.

Abstract conceptual method schemata facilitate application of Systems Engineering's [1] complexity management techniques (e.g. abstraction, hierarchical structuring, analysis of system environment and life phases) during their further concretion from "what" a method is supposed to do, towards "how" this can be achieved. Similarly, bottom-up application of the framework leads from a descriptive process model ("what" is done?) to abstract formulation of fundamental methodical wirkprinciples ("why" is it done?). In both cases, fundamental method mechanisms with regard to information conversion become transparent. This facilitates context-independent selection of existing methods and evaluation of their applicability, and therefore provides an effective interface for their integration into the method development procedure.

Fig. 6 provides an example from the context of customer feedback integration into early stages of innovation processes. Such integration is a complex task, as customer reactions during the product operation stage are subjective in nature and depend on a multitude of interrelated factors, many of whom outside the sphere of influence of the respective company.

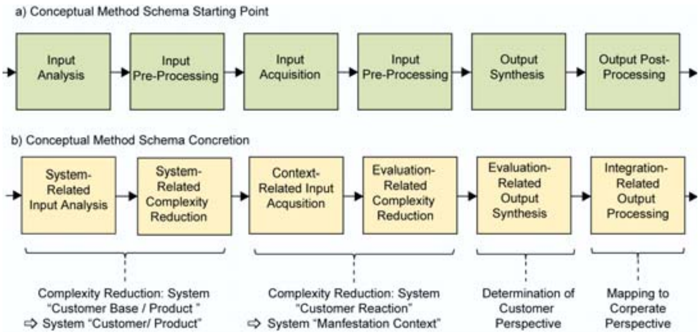

Fig. 6: Conceptual method schemata for customer feedback integration

In this case, based on process interfaces and causes of informational complexity, the conceptual method schema in Fig. 6b outlines a procedure for contextual and function-oriented analysis of customer reactions, and customer perspective integration into early stages of innovation processes.

4 Summary and Conclusion

Management of complexity has become an essential challenge in the current competitive environment. Complexity in the context of the early stages of innovation processes is closely related to properties of the information processed at these stages. Heuristic methodical support of problem solving activities, i.e. information converting activities, can therefore substantially contribute to ensuring and increasing quality in engineering design. Specific requirements of meta-methodical support, i.e. a method for the development of methods, are derived in this paper. Two aspects are particularly relevant in this context: (1) Methods are procedural models of processes, and results of (method development) processes, of which again a meta-method is a procedural model. This implies meta-methodical self-applicability. (2) Method development constitutes a planning problem and as such circular structure of interdependent problem understanding and problem solution.

Consequently, system and model theoretic principles are applied, interpreting methods as both abstract system models and process outputs. This leads to a meta-methodical framework using abstract information converting operations to structure the method development process, and to provide generic, task-independent building blocks for method development. The framework focuses the definition of conceptual method schemata, making explicit fundamental method mechanisms with regard to informational complexity. The framework supports both top-down and bottom-up approaches the development of process models, and facilitates identification and evaluation of existing methods with regard to their integration into future heuristic procedures.

The systemic approach facilitates discursive procedure in method development and operative activities respectively. General validity of this conceptual foundation allows the heuristic methods to consider informational complexity in general, without narrowing their scope from the outset.

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Trends of Evolutions and Patent Analysis: An Application in the Household Appliances Field

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Abstract
This paper describes the results of an experience carried out in the field of systematic innovation. Its main goal has been to verify the validity of evolutionary laws introduced by TRIZ theory applying them to a complex industrial product. The product considered is a washing machine and particular attention has been focused on two sub-systems, the tub and the soap dispenser. The paper, first, describes the patent search activity carried out for both the whole washing machine and the specific subsystems; then their evolutions have been single out and compared with the evolution patterns coming from the formulation proposed by Savransky.

Keywords
Intellectual Property Management, TRIZ, Trend of Evolutions

1 Introduction

The capability to manage Intellectual Property is becoming essential in companies that actively try to face competition of emerging countries and Far East (China, India, etc.). Nevertheless same aspects are still neglected, such as the importance of patents, not only as a legal protection from unauthorised copying of solutions, but as a tool for systematic innovation of products and processes, along with problem solving tools.

The worldwide patents database is the widest collection of technical knowledge ever formalised, on the base of which, since 1946, TRIZ methodology was developed. Actually, the pillars of TRIZ were stated after a merely scientific observation of the inventions described in patents, and became, after decades of refinement, the structured methodology for inventive problem solving we know today [1, 2]. On the other hand, TRIZ tools are used to speed up product/process innovation activities and patents represent the final step of research and development of successful ideas.

The work described in this paper refers to a collaboration between University of Bergamo and Engineering Center of Whirlpool Europe on the theme of product innovation and development. Previous works [3] were focused on the definition of an improved approach for modular design, obtained trough the integration of Design by Variant [4], Design Structure Matrix (DSM) and TRIZ. Anyway, some issues are still to be solved, especially those regarding the criteria used for the clusterisation of subsystems. Thus, the present work has the aim of improving this step through the definition and analysis of the lines of evolution obtained from a proper patent search.

In the following paragraphs authors describe, at first, the way the search has been carried out to define the development of an household appliance form the very early prototypes to the latest innovations published. Thus, the picture drawn has been considered in comparison to the Laws of Evolution of TRIZ to search for analogies and differences. The aim of this activities is of crucial interest for at least two reasons: (a) in literature most of the case studies are not based on such a wide patent search, and are not focused to the evaluation of applicability of laws of evolution to an industrial system, and (b) the exact positioning of current product according to the laws of evolution gives a sharp idea of the challenges to face for wide-ranging further enhancement or to improve modularity.

2 TRIZ and Trends of Evolutions

TRIZ is mainly a methodology for systematic innovation and problem solving. Its underlying idea is that invention has logical rules and principles that lead from problem to solution, i.e., there are common patterns in ways of solving problems that, extracted and coded, technologists and researchers can use to obtain the capability to solve problems creatively. TRIZ has built a system made of abstract principles and laws, together with a huge collection of facts and applications examples in a readably applicable manner [5, 6]. Research in various areas of science and engineering has shown that the general character of system development is essentially the same for any system. While research on the evolution in biology and in economical systems is well established, similar studies on techniques are only now beginning.

G. S. Altshuller [7], Yu. S. Melechenko, and A. I. Polovinkin [8] initiated studies of evolution of technique in the framework of TRIZ in the 1970s. TRIZniks believes that all technical systems evolve according to objectively laws. These laws can be recognized, revealed and then re-used by skilled technicians to perform innovation or to forecast future steps of technology. Assigning evolution trends to a specific system allows us to determinate the most promising characteristics of the next generation of technology and solutions for this system.

Beyond the classic classification of the evolutionary laws, TRIZ experts, such as V. R. Fey [9], D. Mann [10, 11], V. Petrov [12] and S. D. Savransky [13], proposed some variants of the evolutionary laws. In our work we refer to the formulation proposed by Savransky since it's the more structured and it better fits to the context of this work.

According to Savranky's terminology in the followings the concept of product/process/system will be addressed as *technique*. This formulation is based on two postulates for technique evolution: *direction postulate* and *time postulate*.

For the *Direction postulate*, a multidimensional space can be used to study a technique, whose position can be presented through a set of characteristics and parameters of different functions. Position in the parametric space characterizes the state of the art for the technique at each moment of its life. The *Time postulate* for a technique evolution is formulated as follows: *each technique and each subsystem has its own representative time of evolution*. This predicate about non uniform evolution of technical system and technological process is widely used in TRIZ. Actually, it is well established that the difference in subsystems due to uneven evolution is a source of conflicts for the system that TRIZ can address with proper tools.

The knowledge of *paths of evolution* can be useful for finding and ranking solutions of technical problems. The most important of these are single-directional, bi-directional and adverse paths. For further detail see [13].

3 The Case Study: Washing Machine

The product taken into consideration has been a washing machine. This term is generally applied only to machines that use water as the primary cleaning solution, as opposed to dry cleaning or even ultrasonic cleaners. Contemporary washing machines are available in two main configurations: *top loading* and *front loading*. In particular, we decided to analyse the front loading configuration (Fig. 1a) since it is the most common and utilized in Italy and in Europe.

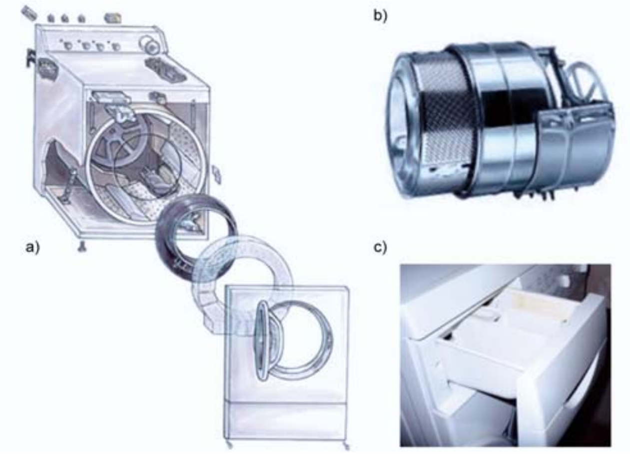

Fig. 1: a) Front loading washing machine, b) Tub, and c) soap dispenser
It is composed by six main sub-systems: the *washing unit*, the *hydraulic system*, the *engine unit*, the *control unit*, the *case*, and the *opening system*.

For our purposes we decided to focus the attention on two subsystems:

- the *tub* (Fig. 1b), a component of the washing unit, because it's a core element of the system. It performs the most important functions of the washing machine, e.g., containing water and cleaning clothes;
- the *detergent dispenser* (Fig. 1c), belonging to the hydraulic system, because it performs different functions considered critical by company's technical staff.

4 Patent Search and S-curve

The tools to carry out patents search constitute the basis of the present work. The purpose is to analyze the patents relative to some subsystems of the washing machine system with the aim to single out their evolution and to compare it with the evolution patterns.

Various on-line databases and tools are available. For our purposes we mainly used *Esp@cenet* (ep.espacenet.com) the patent search tool provided by the European Patent Office. For patents published before 1900, we preferred to use *Uspto* (www.uspto.gov) database because it's more complete. *Uspto* database includes patents published in the United States from 1790. We used also *Delphion* (www.delphion.com), *PatBase* (www.patbase.com), and *Goldfire Innovator* (www.invention-machine.com). Goldfire Innovator has been considered since it is one of tool based on TRIZ methodology.

On the basis of the patent search results the stages of the product life cycle have pointed out. Graphs have been drawn on the base of the number of patents published every year from 1900 to 2005 for washing machine and from 1920 to 2005 both for the tub and the detergent dispenser. From the figures obtained for the whole system, plotted in Fig. 2, it can be deduced that since the S-curve obtained is complete product development has reached maturity. In particular, the stages of birth and childhood go from 1900 to 1940, the growth one continues since 1980s when maturity begins.

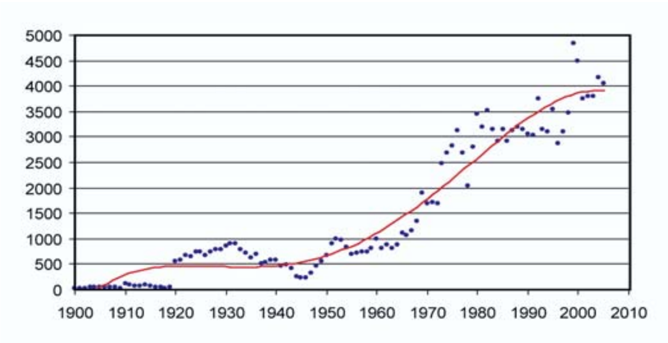

Fig. 2: Number of patents relative to Washing machine from 1900 to 2005

The S-curves drawn for *tub* and *detergent dispenser* sub-systems are very similar. The increasing number of patents could suggest that the subsystems are still in the growing stage; however, further investigations pointed out that the increased number of patents were characterised by a lower level of innovation, typical of mature products. Therefore as in the case of whole system, we could proceed to a complete analysis of the evolution of the product.

5 Identification of Trends of Evolutions

5.1 Tub Trends of Evolutions

With regard to the *Tub*, first an evolutionary tree, based on development variants and chronological order of patents publication has been drawn. Then, on this basis, we started to analyse and single out evolutionary trends. The step existing between a key innovation and its relative prior art allowed us to better understand which were the trends followed by the subsystem “tub” according to TRIZ perspective.

An example is represented by a mono covering in wood (mono-system) (US1389090, 1921) (Fig. 3). The following evolution, of great importance because it is the base of modern washing machines, was the subdivision of the covering in two parts (GB176198, 1922): the tub and the drum, situated inside the tub; thus we singled out a trend of expansion. In other words the number of useful functions increase with the number of the subsystems. Afterwards the tub had a different evolution with regards to materials adopted, such as ceramics, enamelled and stainless steel and plastic (e.g., Patents US3477259 1969, GB1212043, IT1067355 1976). Material change is in according to the second group of the Direction Postulate; in particular to the "New Materials" trend. The use of new materials with better property is finalized to the improvement of the performances and the increase of the useful functions.

As an example, the ceramic materials led to the reduction of the noises and to smaller heat dispersion, diminishing the warm up times of the washing water and the use of energy. The use of the steel allowed greater resistance but it worsened of some useful functions and provoked some harmful functions. This kind of tubs, actually, must be thick in order to resist to the mechanical stress, and are characterized by the presence of numerous weldments.

The next evolution is the introduction of a shell fitted over a casing and it represent another example of expansion trend. The new element allowed to manufacture thinner stainless steel tubs and to reduce weldings.

Proceeding in the same way all evolutionary trends have been identified (Fig. 3). The main trend that emerged is the expansion-convolution one (main path). At first, actually, the tub expanded with the addition of new elements. As described above, the first patent is relative to a mono piece wooden tub; then the drum was introduced; subsequently new elements were added, such as the shell fitted over the casing, the carrying structure and the reinforcing metal ring.

The result of this first part of the evolution is the formation of an efficient device, but much more complex then the starting one. The second part of the trend is represented by a phase in which the number of elements and subsystems decreases. As an example, the introduction of plastic allowed to eliminate the weldments and, consequently, the supports for the suspensions. In the last stage of this evolutionary pattern we found the attempt to merge two subsystems into a single one carrying out the same functions. A washing machine with the tub joined to the external structure would increase the load factor maintaining constant the external dimensions. The most recent and extreme solution propose a tub integrated in the external case and a new technique of active balancing of the load.

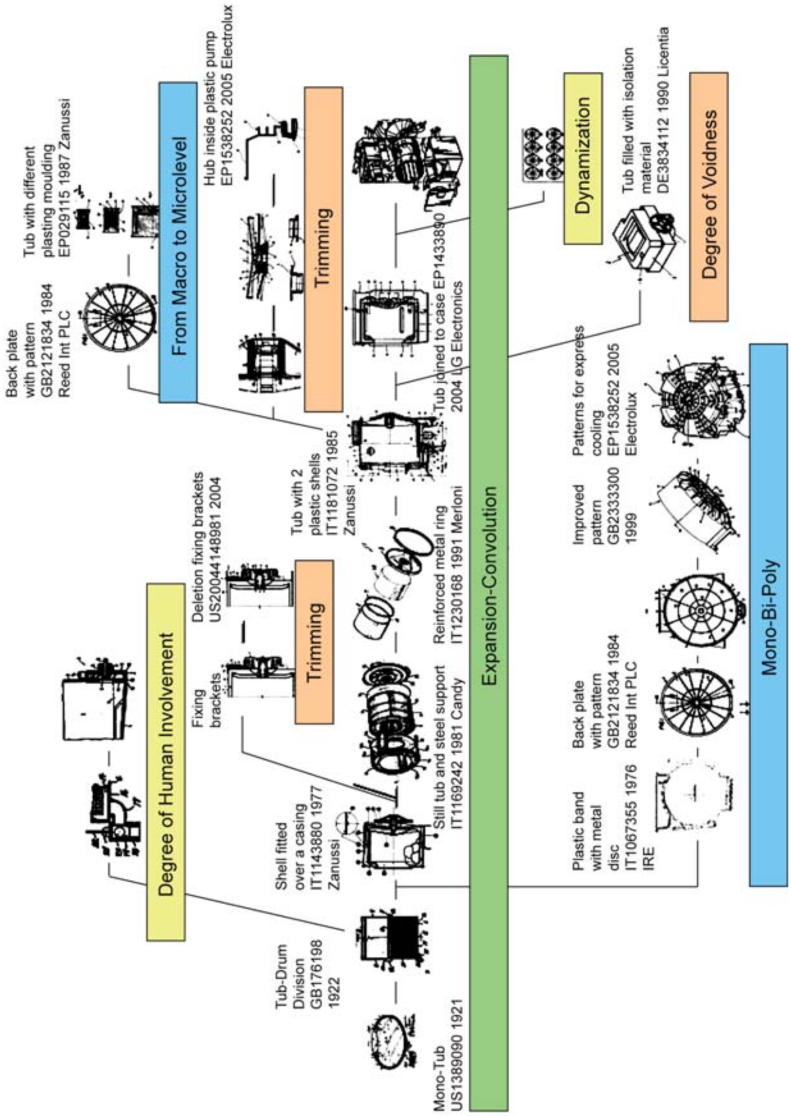

Fig. 3: Tub Trends of Evolutions

This solution starts another branch, characterized by the trend of dynamization. Finally, it has been observed how the process of convolution has lead to an increase of the ideality through the reduction of the number of auxiliary subsystems and elements.

After the main path of evolution of the tub was identified, some minor branches were identified. The first one follows the trend of decrease of human involvement. In other words the subsystem increased its own ideality with the reduction of human participation. Initially, in fact, the tub was filled up and emptied manually; with the introduction of the drain valve, the phase of emptying became very simpler and automated. At last with the introduction of the pump, all the process became automatic. The second branch is based on the trend mono-bi-poly and it is relative to the pattern of the back plate. Initially the tub didn't have this kind of profile because it was made of steel, which is not sensible to thermal stress due to washing cycles. By the way, with the introduction of plastic it became necessary to add reinforces (e.g. ribs) with the function of strengthening the structure avoiding deformations. Then the surface pattern became more and more complex, improving the performances of the demanded function.

Three branches follow the trend of trimming. The first one is relative to the elimination of the support bracket that holds the lodging of the drive shaft. This innovation leaded to an improvement in terms of space and ease of manufacturing. The second is about to the hub subsystem, that it has the function to support the drive shaft. This element was simplified eliminating components like screws and pins. Today, the hub is embedded in the plastic tub. The last trend of trimming refers to an innovative method of joining the plastic parts eliminating the use of metal clips.

Last two branches represent the trend of transition to micro-level and the trend of degree of voidness. The first one is relative to the use of different materials for specific details of the tub that improve the resistance of the subsystem to mechanical stress. The second one is about a new type of tub where the ballast is constituted by powder or iron scraps. In this way empty spaces between the particles are created with the aim to increase thermal insulation.

5.2 Detergent Dispenser Trends of Evolution

For the entire detergent dispenser it was not possible to determine general trends. This is due to the fact that this subsystem provides several different functions and the development of the devices composing it is not equal. By the way a further decomposition of the detergent dispenser into functional groups allowed us to detect branches following TRIZ trends.

The functional groups chosen are: reservoir, selection of the compartments, detergent measurement, storage and conservation of the detergent, rinsing of the compartments, independent devices for detergent dispensing and devices for water recycling. As an example we will describe the evolution of the reservoir.

The main evolution trend emerged is mono-bi-poly. As we can see in Fig. 4, at the beginning (US1991911) there was a reservoir with only one compartment; later the compartment was divided into two, three and four parts (GB1168466). Then we found another trend represented by a short branch. The two main patents that characterize this branch describe inventions whose aim is to use the same chamber for detergent in either powder or liquid form. The trend, on the basis of this evolution is dynamization. As an example patent IT1204920 presents a chamber with a movable wall.

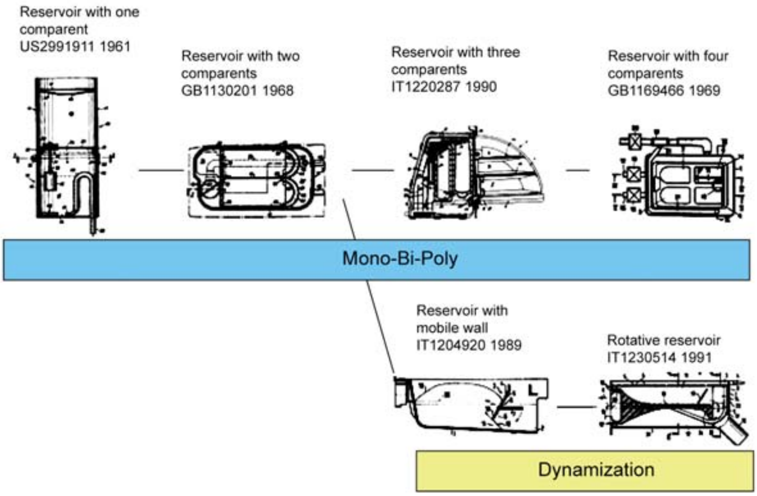

Fig. 4: Trends of Evolutions for Reservoir geometry

6 Conclusions

This work reports a wide range study on the applicability of TRIZ Laws of Evolution to a one hundred years patent-driven model of development of a technical system. Synergies among TRIZ, patents and evolution of technology is one of the most challenging issue Trizniks are facing in this years, because of the extremely high potentiality that new tools in this field can express. Actually, the capability to master problem solving tools, to manage intellectual property and to forecast potential future technological evolutions give a dramatic competitive advantage to those companies considering innovation a must. This paper shows the way trends of evolution can be highlighted through a proper use of patent search tools – also available for free. This opens a number of possible future exploitation of the results obtained, and not last, to speed up innovation, with the ideal final result to make it efficient and lean.

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Understanding the Link between Aesthetics and Engineering in Product Design

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Abstract
Industrial design and styling is the activity associated with aesthetics and the evocation of human emotion through manufactured products. In today's cost competitive global markets industrial design and styling is a significant lever in distinguishing products from others to potential customers. This paper investigates the current state of practice and research in linking aesthetics with engineering design. With the help of a case study, the research identifies major issues in the integration. The research also highlights the potential problems and opportunities for the integration of requirements, concept design, industrial design and styling via software.

Keywords
Aesthetics and Styling, Engineering Design, Product Design and Computer Aided Design (CAD).

1 Introduction

The aim of this research is to investigate the relationship between the interests of aesthetics and engineering during the design process and the tools potentially capable of forming a "Link" between the two. The aim is achieved through the three objectives of:

- primary research of industrial visits and interviews with practitioners
- secondary research by means of a literature review
- a case study utilising two Industrial Design and Styling software tools in the design of a domestic kettle

The “Link” between aesthetics and engineering in design is found to be dependant on several factors. Typically these factors range from market sector, cost reduction needs, manufacturing processes, technology (Roy et al 2002), customer requirements, customer satisfaction, to the value placed on emotional influence of product design, and even philosophical issues about the human condition (Liu 2003). McKim has uncovered advantages of a design process that coherently links aesthetics and engineering design into one aim. Such an aim becomes a single methodology which is not dissected into one or the other during design decisions.

It is often essential for companies today to deliver more customised products with shorter lead times, perfect quality and reliability and at lesser prices in order to maintain Competitive Design. A typical design process focuses on the product’s overall required functional specification provided by the customer, to produce a set of embodiment designs capable of obtaining this function (El-Ganzoury et al 2006). The design is effectively accomplished by focussing upon maintenance of the aesthetic characteristics of the product.

The concept design stage potentially provides the most opportunities for creativity and innovation during the design process (Jin et al 2005). In addition it has been indicated from a variety of studies that over 70% of the manufacturing cost of a product is determined during the conceptual design stage (Shehab and Abdalla 2002, Roy et al 2001). In comparison the design phase itself accounts for only 6% of the whole product lifecycle development cost (Gayretli and Abdalla 1999).

Manufacturers are seeking to improve their product offerings by developing new value based designs; by this the manufacturers are attempting to provide a better link between the aesthetics of the design stage, the engineering and the concept realisation all the way to the manufacture (Giannini et al 2006).

2 Capturing the Aesthetics: Results of a Questionnaire

The research methodology focussed on a number of companies via a semi-structured questionnaire. In addition several case studies were presented by industry through industry events or industrial visits. Table 1 provides example questions and responses from the questionnaire. It is found by this research that the aesthetic input is an increasingly important aspect and must take place at the start of the design. This process is inspired by requirement lists from the company, magazines and design shows. It is further enhanced by an awareness of the market and associated tools for such awareness. The aesthetics become iteratively developed as the designer sits and works through the design. Important inspiration from a process of Lifestyle Analysis leads to appreciation of aesthetics and the development of a desirable product.

A significant observation made was that during projects the aesthetic appeal could possibly come from another product or designer in a cross fertilization process. This was useful because it allowed the incorporation of the latest technologies and materials in all of the design projects. However there is always a lot of aesthetic input from past experience, which can be through everyday life or specific situations that spur the designer towards preferring one design decision to another.

Design processes are different between companies and also projects. This is significantly more apparent for the companies which prefer to promote the brand of the product as their identity. In such an instance the brand can be an aesthetic aspect or quality of the product, making it prominent on the shelf in comparison its competitors.

Manufacturing of today's products is increasingly based offshore resulting in several communication challenges between both the design companies and the manufacturers. This is often because the manufacturers are required to adapt the products for safety reasons or because some manufacturing processes produce associated changes which are often not aesthetically pleasing. Manufacturers often do not approach the product from the same direction as the designers.

Sometimes it was observed that engineering analysis activity provided several alternatives for material weight reduction or redistribution. In this case the alternative which was most aesthetically pleasing was taken. Clearly in these cases engineering design took priority during optimisation.

A problem found was that it is not easy to demonstrate the immediate advantages of the aesthetics for the product as a total when faced with the resulting engineering changes they cause. Problems can be caused because the engineers are often not open to the new techniques and ideas presented by the designers. Due to tradition and lack of up-to-date knowledge the result is a knock on effect for the designers in terms of time-to-market and therefore product development. This is a potentially important area which might be addressed in further work.

Tab. 1: Example questions and responses to the questionnaire

Example Questions	Example Responses
What do you believe is the difference between aesthetics and engineering design?	"They are both part of the same goal but they are different goals for each one", "Aesthetics comes from engineering as much as engineering comes from aesthetics"
What is your definition of a good aesthetic design or product?	"Does the job with a degree of style to it", "Generates an emotion in someone", "Gives them passion or enjoyment rather than being a lifeless lump of materials"
How do you find maintaining aesthetics through the design life cycle?	"Often very time consuming", "Constant contact with the engineering sector via e-mail and phone", "Sometimes things have to be changed to make it work better in production"

Therefore a potentially key aspect of the "Link" is for the design engineer to maintain the aesthetics of the product throughout the development lifecycle and have the same aesthetic qualities at the final product presentation as at the first concept presentation. Clearly this is not an easy task when considering the previous discussion.

It was found in the research that one way to capture and present the product aesthetics is to have a prototype built after the sketching process is approved. This provides a tangible item for the purposes of a "real feel" for the scale and the properties of the product.

For two of the companies, direct contact with the buyer is a vital tool during design development. The buyers are aware of the requirements of the company and also the market trends and can assist with the product branding. It is important for the designers to approve and justify their decisions to the customer allowing the development of the product. This was best displayed with hand sketches and rendered drawings and was not often done with software tools.

For the companies that actually used software they felt it was merely a presentation tool and did not help design or capture the aesthetics of the product. This was because software was described as being too slow and limiting of the designer's creative ability.

3 Validating the Design

At key points of the design process there are stages of validation. The companies contacted use different methods to validate their designs. For example the identification of the user and how the product performs for that user. A fundamental question uncovered which the designers felt that they must ask themselves is: will it sell?

Past experience of manufacturing techniques and materials plays a large part in the validation and can easily be applied to new products. For one company the client has the final word as they are the resources and the backing for the product. This can cause problems as they often do not have the same idea for a product as the designer. The designer must prove his process and design in a series of meetings and presentations.

A situation not sufficiently documented is when a designer makes a decision to create a completely new style, material or finish that they feel works. This is difficult to validate to the customer because it can come from gut feeling and initiative. This can also be known as creative freedom that is often lost in the scramble to fit the market requirements and hence compete.

4 Identifying the Link between Aesthetics and Engineering Design

A preferential product has been described as a product which satisfies requirements with a degree of style, so that appropriate emotions can be generated in the user. It can be contended that one of the most important realisations is that a preferred product must push design forward and challenge the industry, not just accept the boundaries.

In order to achieve this, research has identified from the literature and also a semi-structured interview, an apparent "Link" between the main areas of aesthetics and engineering design in the product development life cycle.

It has been found that aesthetics is an integral part of the process of designing a product. In order to design a competitive product it is necessary to have a familiarity with the engineering and complexities it involves. Once these complexities are understood it is possible for the designer to challenge them and so to improve the aesthetics.

The aesthetics are informed by the technical aspects of the product and in some situations this can be vice versa. It is important to remember that the function and aesthetics of the product are paramount; resulting in some designs which work well but appear dull and some beautifully designed products which do not work so well.

Aesthetics and engineering have the same ultimate goal of succeeding; however there may be different sub-goals for each in the same product. Ultimately the two should work together and therefore this is a potentially significant area.

The engineers need the support of the design engineers and the design engineers must be aware of the engineering limitations. Product designers of today are bridging the gap between the marketing and the engineering teams aiming to produce a desirable functional product.

Finally some example generic responses from the interviews are found below:

- “It is very important that life style analysis leads to aesthetic appreciation and the development of a desirable product”
- “The brand can be an aesthetic aspect or quality of the product, making it prominent on the shelf against its competitors”
- “The aesthetic input is a vital aspect and must take place at the start of the design”
- “Aesthetic appeal may come from another product or designer in a cross fertilization process”
- “Software was merely a presentation tool and did not help design or capture the aesthetics of the product”
- “Engineers stick to traditional techniques”

5 Case Study – Design of a Domestic Kettle

In order to further understand as much as possible the product design lifecycle a case study was undertaken. The case study explored two current state-of-the art software tools and design process tasks. The aim was to take a product completely through from the sketch and initial ideas stage, to the latter prototyping stages whilst aiming to maintain the aesthetics initially defined in the product. Maintaining the aesthetics definition was deemed to be important since this was highlighted by the company interviews. For example as the product passes along its design lifecycle it is adjusted and changed for numerous reasons. These adjustments are not always sensitive to the aesthetics and without close observation and checking by the design teams, there is a possibility that the final product would finish in a very different form from that of the initial concept.

This case study looked at the process and the areas that are involved so as to identify the role software can play by being used to display and highlight the aesthetics quickly and dynamically.

The first step used was in defining the product requirements, recorded in a Product Requirements Specification document (Pugh 1993). Example categories for the product design requirements were: functional, usability, technical and environmental. The functional requirements included: the kettles balance, the kettle handle's orientation, volume of water held, how the kettle poured water and how hot the kettle was on the outside.

The second step was the conceptual design. Initially a number of sketches were made resulting in a final one as shown in Figure 1. Some of the raw creativity of the designer is found in this example.

Tab. 2: Excerpt of Design Weighted Matrix

Criteria	Importance Rating	Concept 1	Concept 2	Concept 3
Response to PDS	5	+	+	+
Aesthetics	5	+	+	+
Wireless	5	+	#	#
Material	2	#	#	#
Safety to user	5	+	/	+
Ergonomics	3	/	/	/
Performance Ranking		1	2	3

Once the concepts were sufficiently developed, a Design Weighted Matrix (DSW) was used to directly compare concepts via the chosen criteria. The DSW is shown in Table 2.

The DSM is a simple but systematic method which precludes a designer somehow "falling in love with his design", as observed by a respondent to the questionnaire earlier employed. It was found that aesthetics and function were concurrent considerations. The rating of aesthetics was found to be highly subjective and in need of a systematic approach to preclude the effect of personal preferences.

A final design was found as shown in Figure 1. This was developed in software. Respondents to the questionnaire highlighted the problem of decision makers in companies being unaware of the potential capability of software. The software used was an existing typical Computer Aided Design (CAD) package with aesthetics modelling capability and also a different kind of CAD package suitable for a limited range of design activity, here being aesthetics creation. Different in that it used virtual clay modelling facilitated through a haptic device (Krause and Biahmou-Tchebetchou 2005) and the technology of Voxels, a combination of volume and pixels.

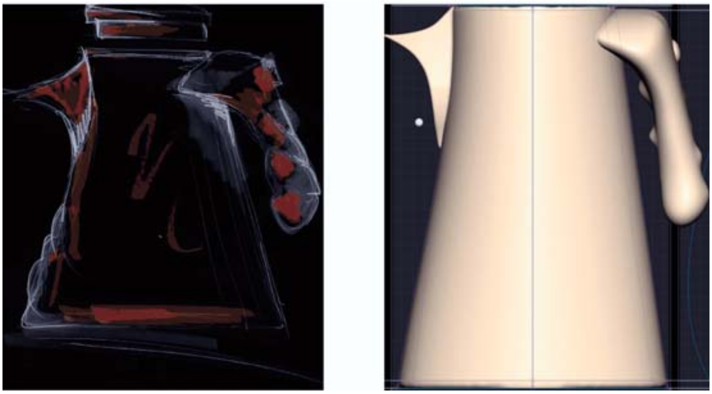

Fig. 1: The Final Concept Sketch and the Virtual Clay Model

The software packages were suitable or not suitable for the "Link" in several ways. The virtual clay modelling tool allowed rapid development of product concepts but precluded engineering analysis methods. The CAD package allowed concurrent modelling of geometry with analysis and assembly modelling within the same software. The "Link" was through a central model concept linking all applications. The virtual clay modelling tool was easier to learn and apply quickly and allowed rapid "what if?" decisions for aesthetics. This potentially allowed a "Link" between engineering back to aesthetics. The virtual clay modelling tool was potentially more intuitive in model development through the analogy with sculpture and use of the haptic device.

6 Discussion

This research develops an AS-IS model of the "Link" between aesthetics and engineering in design. The main findings of a series of semi-structured interviews with industry, a literature review and a case study can be made. It is found that in practice aesthetics and engineering are not considered together. Aesthetics are a challenge to maintain during engineering design. Even so aesthetics can be the main differentiator between products when all else is equal. The "Link" has been found to be many things. The "Link" can be to maintain balance of all factors. It is also directed by the "human needs" of the design. The "Link" forms a restricted set of design alternatives. The "Link" is enabled through specific geometrical entities modelled in software and involving a universal method of communication between all design functions. The "Link" can contradict manufacturability, and therefore may motivate new manufacturing processes. The "Link" is influenced through the timing of the design development stages, leading to terms such as "link being lost from concept through to manufacture". The "Link" can be obtained through the selfish concern of particular design engineers. Scientifically the "Link" can be inspired through modelling nature, or using nature driven engineering principles. The "Link" can be through the use of materials, through the education of the design team, or through the process of associations. The "Link" requires a larger shared solution space to be improved. Cross fertilization across the "Link" can inspire new solutions, for example through materials. The "Link" is inspired through people, lifestyle, balance, simplicity, for example through reductionism, and tactile feel. The sketching and prototyping activities are a main source of development of this area. Finally aesthetics are a source of progress and innovation.

7 Conclusion

An AS-IS model has been developed describing the "Link" between aesthetics and engineering design. Activities such as structural analysis and development of function are linked with concepts of look, feel, emotion and subjective appreciation of the product. Several concerns have been raised through comments from industry, the literature and a practical case study with Computer Aided Design software. Practical concerns such as offshore development, materials and manufacturing processes have been highlighted. But also optimisation, design activity issues and human factors in conducting design explored. The "Link" is found to be a potential area for development in new value adding for products and is also motivated through philosophical debate.

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Preliminary Study of Cognitive Model of Designer's Creativity by Using Formal Protocol Analysis

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Abstract
Protocol analysis is an important approach to studying designer's thinking process and problem-solving behaviours. Although protocol analysis has been used in a lot of research to understand designer's cognitive activities in the design process, a systematic procedure is needed that can be used across different experiments. This paper proposes a protocol analysis study based on the concept of design state. A design process is composed of a series of design states. An experiment is conducted to collect protocol data about a product design, from which design states are extracted. The preliminary analysis of the protocol data shows that a designer generally considers more environment components and their deeper relationships in delivering a key concept.

Keywords
Protocol analysis, cognitive model, environment-based design, design creativity

1 Introduction

Since the 1960's, research activities in design theory and methodology have attracted a lot of attentions from different areas including engineering, computer science, philosophy, and psychology. As a result, different theories and methodologies have been proposed, such as general design theory [1], systematic design methodology [2], axiomatic design [3], formal design theory [4], and axiomatic theory of design modelling [5]. However those design theories and methodologies must be implemented by a designer in order to deliver a design solution. To follow a design methodology is a logical and rational process while designers' thinking and problem-solving behaviour is an intuitive and imaginative process. Those are two contrasting processes. To reduce the discrepancies between traditional design methodologies and designer's freedom of creation, it is critical to integrate designer's cognitive processes into the design methodologies. Our ultimate goal of this research is to develop robust design tools, which are composed of logical procedures that may naturally assist the human creative and innovative design processes.

The development of the robust design tools mentioned above must be achieved through the thorough understanding of designer's thinking and mental processes, which shall uncover what and how decisive factors affect a designer's decisions. Protocol analysis is a prevalent method in the current research to identify the role of designer's thinking and reasoning in the design process [6 - 9]. This method studies a subject's mental processes in accomplishing tasks by recording their spontaneous thinking aloud as running commentary, which will be subsequently segmented into the discrete atomic mental operations [10]. There are two major approaches in protocol analysis to collect protocol data: concurrent verbalization and retrospective verbal report. The method of concurrent verbalization requires subjects to talk aloud what they are thinking as they go about trying to solve various problems. In contrast, the method of retrospective verbal report will leave the designers alone without any interference before they have completed their design tasks. The designers will then be asked to recall their design process and be reminded to answer some questions if they miss any information. Some researchers have argued the effectiveness of these two approaches [11, 12].

The studies of protocol analysis in design have been growing increasingly since the 1980's in investigating the process of designing and in understanding how designers design. Those studies have shed some lights on how protocol analysis method can be used to analyze designer's cognitive processes and problem-solving behaviours. They have extraordinarily advanced our understanding of design. However, the experimental set-up and the interpretation of protocol data heavily influence the outcome of the protocol studies. Most of the protocol analysis methods are developed based on specific domains, individual design problems, or researcher's experience. It is hard to compare these protocol analysis methods and to apply them into other practices. Therefore, it is essential to establish a systematic and more objective approach of protocol analysis to further study designer's cognitive processes.

The aim of this paper is to develop a novel protocol analysis approach based on the axiomatic theory of design modelling [5]. The approach follows the evolutionary nature of the design process and can be applied to the general design problems. The rest of this paper is organized as follows. Section 2 introduces a mathematical representation of the evolution process of design by using the axiomatic theory of design modelling. Section 3 proposes the protocol analysis method. Section 4 discusses our preliminary results of the protocol analysis. Section 5 presents a summary and the future work of this research.

2 Evolutionary Design Process and its Mathematical Representation

Our protocol analysis approach is developed based on axiomatic theory of design modelling [5]; hence, it is essential to briefly introduce this theory before we discuss our protocol analysis. The axiomatic theory of design modelling [5] provides a formal approach that allows for the development of design theories following logical steps based on mathematical concepts and axioms. The details of axiomatic theory of design modelling can be found in [5]. A key concept in the axiomatic theory of design modelling is the structure operation, which can be defined as follows:

Structure operation, denoted by ⊕, is defined by the union ∪ of an object O and the interaction ⊗ of the object with itself.

$$\oplus O = O \cup (O \otimes O), \tag{1}$$

where ⊕O is the structure of an object O.

In the axiomatic theory of design modelling, everything in the universe is an object; therefore, an object may include other objects, the relationships between objects are objects, and a process is also an object. The structure operation provides the aggregation mechanism for representing the evolution of objects in the design process. Based on the structure operation, the concept of product system can be defined.

A product system is the structure of an obje ct (Ω) including both a product (S) and its environment (E).

$$\Omega = E \cup S,\ \forall E, S\ [E \cap S = \Phi], \tag{2}$$

where Φ is the object that is included in any object.

The product system ($\oplus\Omega$) can be expanded as follows:

$$\oplus\Omega = \oplus(E \cup S) = (\oplus E) \cup (\oplus S) \cup (E \otimes S) \cup (S \otimes E), \tag{3}$$

where $\oplus$E and $\oplus$S are structures of the environment and the product, respectively; E$\otimes$S and S$\otimes$E are the interactions between the environment and the product. A product system can be illustrated in Fig. 1.

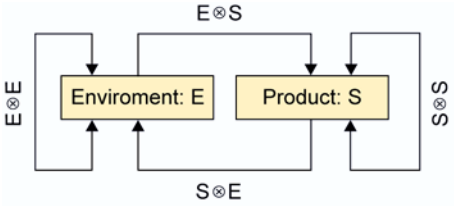

Fig. 1: Product system

The design process can be represented by design governing equation [13],

$$\oplus\Omega_{i+1} = D_i(\oplus\Omega_i). \tag{4}$$

The design problem evolves along the evolution of the product. At each stage of this evolution process, the design problem is defined by its current product system $\oplus\Omega_i$, which is called the state of the design. The components of product system $\oplus\Omega_i$ keep on changing while conflicts exist in $\oplus\Omega_i$. This evolution process of design can be illustrated as in Fig. 2.

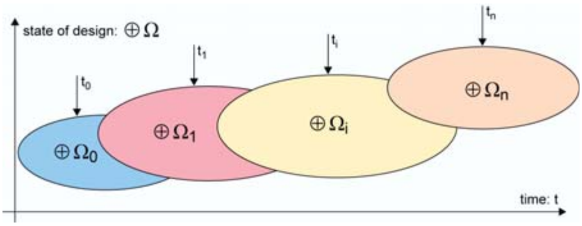

Fig. 2: Evolution of the design process

The evolution process of design can be stated in the following theorem [13].

Theorem of Dynamic Structure of Design Problem. In the design process, design solutions to a design problem may change the original design problem, if the design solutions are different from their precedents, either by refinement or by alteration. This nature of the design problem was originally proposed by Zeng and Cheng as the recursive logic of design [14]. This logic indicates that design is a process recursively generating design solutions and the knowledge to evaluate the solutions. The evaluation knowledge indeed defines the design problem. This result was confirmed by Roozenburg's research [15]. Later Maher, et al. [16] used the gene concept with the recursive design process and pointed out that the problem space and the solution space co-evolve together, with the interchange of information between the two spaces. Observing from some protocol data, Dorst and Cross [17] indicated that creative design is a co-evolution process that looks for problem and solution at the same time. Now design has been widely recognized as a process of co-evolution of the problem state and the solution state.

3 Methodology

In this section, the details of the protocol analysis method will be explained. An experiment is used to illustrate each step of the method. The protocol analysis includes the experiment set-up, transcription, segmentation and encoding, and the evaluation of the design solutions.

3.1 Design of Experiment

In this experiment, we have adopted the design problem used by Dorst and Cross [17] since we believe that this problem is feasible, realistic and challenging for the subjects. We have rephrased it so that it is more understandable to our subjects. This design problem is "to design a litter-disposal system for the passenger compartment. This system should be convenient for the passengers to deposit garbage and meanwhile it is easy for the cleaners to collect the garbage." The structure of the passenger compartment is also shown to the subjects. Since it is difficult to determine the number of subjects in human factors study, different numbers are used in different experiments. Seven graduate students with various working experience (5-10 years) are taken as the subjects in our experiment. They are from different backgrounds, such as mechanical engineering, electrical engineering, and computer engineering. All the subjects have learned one or two design methodologies.

The experiment includes design session and retrospection session. In the design session, subjects are left alone in a quiet room to solve the design problem. They are asked to draw or write anything on a tablet screen. The subjects can use dictionary or Internet to find the required resources. The experimenter can answer any direct question from subjects. In the retrospection session, subjects are asked to recall and report what they were thinking at each step of their design process by watching the videos of their actions and the screen activities. If the subjects miss any information, they will be reminded or asked to clarify their problem-solving behaviours. In the two sessions, three webcams are used to record the entire process from different angles. The three webcams can record the audio and video information. The activities done on the tablet screen by subjects are recorded by the software "My Screen Recorder". This software can record anything that subjects draw or write on the screen of the computer. In this way, the subject's activities can be completely and accurately recorded by the three webcams and the software of "My Screen Recorder". Then the protocol data will be organized from the video and audio media and screen recording video for further analysis.

3.2 Transcription

After the experiment is conducted, we need to transcribe all the words spoken by subjects during the retrospective stage into text documents. The text documents may contain some vague and inconsistent information. Moreover, subjects may not give enough information to explain their thinking process just by showing their intentions, so we need to add some annotations to explain their non-verbal intentions to make the transcript more consistent. Hence, we have three operators to do cross-checking in order to ensure the accuracy and consistency of the transcript. Finally, we get the formalized transcripts. Below is an example of the formalized transcript.

"Now I consider the convenience for the cleaner to pick up the garbage bin. Cleaners walk along the aisle. Then I think to put the garbage bin under the table. It will affect the movement of the passenger's legs if the garbage bin is put under the table. So the only place is under the seats. Put here (under the seats). These are seats, tables (point to the sketches on the screen). This place (under the seats) is not convenient for picking up. Here, I feel it is not good. So, I consider putting along the side of the seats close to the aisle."

3.3 Segmentation and Encoding

Considering the theorem of dynamic structure of design problem, we will identify each design state in the design process to segment and to analyze the protocol data. The concept of design state will be used in our experiment analysis as the basic unit for the segmentation of protocol data.

After we get the formalized transcripts, we need to divide each subject's transcript into segments and then the segments are encoded using our coding scheme. As mentioned above, a design process is characterized by a series of design states, so each transcript can be divided into separate design states. A design state represents a single intention of the designer. It can be identified as any concept generated or modifications of previous design states.

Encoding is an important and critical part to analyze subject's protocol data. Design process proceeds with the evolution of design states. So we will take each design state as the basic encoding unit. A design state (DS) is represented as $\oplus\Omega_i$, which can be decomposed into the structure of the product, $\oplus S_i$, the structure of the environment, $\oplus E_i$, and their relationships, $B_i=(E_i\otimes S_i)\cup(S_i\otimes E_i)$. An environment may contain several environment components:

$$E_i = \sum_j e_j.$$

We use R(a,b) to represent the relationships be-tween two objects and it can be applied to multiple object relationships. Below is an example of one segmented protocol.

Protocol 1: "Now I consider the convenience for the cleaner to pick up the garbage bin. Cleaners walk along the aisle. Then I think to put the garbage bin under the table."

e_1=cleaner, e_2=garbage bin, e_3=aisle, e_4=garbage, e_5=table

$E_1=e_1\cup e_2\cup e_3\cup e_4\cup e_5$

$b_1=R(e_1, e_2)$: Cleaner picks up garbage bin conveniently.

$b_2=R(e_1, e_3)$: Cleaners walk along the aisle.

$b_3=R(E_1, S_1)$: I think to put the garbage bin under the table.

$B_1=b_1\cup b_2\cup b_3$

S_1= the location of the garbage bin is under the table.

3.4 Evaluation of Design Solutions

In this paper, environment-based design [13] is used to analyze the design problem. First, we find out all related environments about the product to be designed from the design problem description. There are seven major environment components: train, compartment, cleaner/garbage collector, railways/user, manufacturer, passenger, and garbage. Then we analyze all relationships between the environment components and the system to be designed. We can get the design requirements as follows:

R1: *The system should be convenient for the passengers to deposit garbage;*
R2: *The system should be easy for the cleaners to collect the garbage;*
R3: *The system should fit the structure of the compartment;*
R4: *The system is used in the train and should keep static when the train is moving;*
R5: *The system should be acceptable for the railway company;*
R6: *The system should be produced to fit the requirements of the manufacturer;*
R7: *The system can contain different garbage deposited by the passenger.*

Two assessors evaluated the results of the design solutions of the seven subjects. According to the importance of the product requirements, weighting factors are given for the above requirements as 0.2, 0.2, 0.2, 0.1, 0.1, 0.1, 0.1, respectively. The design solutions are scored by reviewing the transcript, segmentation and encoding, as well as any writings or drawings by the subjects. The assessors give the highest score (10) if a requirement is satisfied well and the least score (1) if a requirement is not satisfied. We think that it will be a creative design if all requirements are well satisfied. A total score is given as:

$$M_i = \sum_{j=1}^{7} w_j S_i^j$$

w_j is the weight for the j^{th} product requirement; S_i^j is the score of the j^{th} product requirement for the i^{th} subject. The average scores from the two assessors will be used as the final results. The design solutions are ranked from creative to non-creative as S1, S7, S6, S3, S4, S2 and S5. The two assessors concur that the solution of subject 1 is a creative design.

4 Discussions

In this experiment, the hypothesis we had was that in a creative design, designers consider more environment components and deeper relationships in delivering a key concept. The objective of proposing and testing the hypothesis is to understand what factors could stimulate designers to generate creative design.

In every design, there must be a key concept, which is critical for the designer to decide the final solution. We analyzed the key concepts of all subjects. Fig. 3 shows the number of environment components and the number of relationships in delivering the key concepts of all the subjects. From the figure, we can see that subject 1 considered the most environment components and relationships. Although subject 2 considered 5 environment components in that design state, he did not figure out all relationships between these environment components and the product. In order to deliver a good concept, a designer must recognize all related environment components and figure out their relationships between environment components and the product. So from these comparisons, we can suggest a designer first try to collect the possible environment components, and then figure out their relationships. Even when we get a concept, we can evaluate the concept by analyzing the relationships between the concept and other environment components.

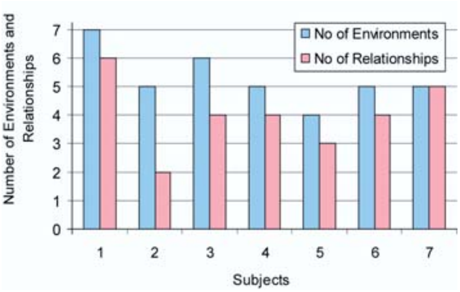

Fig. 3: Comparisons of the numbers of environment components and relationships between subjects

5 Conclusions and Acknowledgement

This paper proposed a protocol analysis study of investigating the cognitive model of designer's creativity based on a theoretical framework. The protocol analysis includes experimental design, transcription, segmentation and encoding, evaluation of design solutions. Then we discussed the results of protocol analysis. The results show that designers should consider all related environment components and think deeper relationships between environment components and the product in order to deliver a good concept. In our future work, more results will be organized and analyzed to find the factors leading to a creative design.

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Results of an Industry Survey on the Application of Dependability Oriented Design Methods

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1 Introduction

Mechatronic systems combine the advantages of mechanical engineering, computer science and electronics, especially with regard to the innovative performance of advanced functions. This leads to intelligent and frequently complex systems whose remarkable functionality is, however, quite often accompanied by the risk of poor reliability or even safety. These aspects are frequently subsumed under the heading of dependability, especially in the field of information technology (Laprie 1992). In order to determine the present state of the application of dependability oriented design methods, an industry survey was made, whose results will be presented. Adapted from these results, the paper sketches an approach of a "design for dependability".

Main results of the survey are presented in this paper. In particular, investigations of most practiced methods in industry and future requirements for the "design for dependability" provide important issues. For example nearly 80% of the companies suppose that the use of methods for dependability will increase. In contrast only a few companies integrate these methods into their design process yet.

In order to cope with this challenge it is suggested that design guidelines, like e.g. VDI 2206 "Design Methodology for Mechatronic systems" shall be complemented by taking dependability into account. The present paper sketches an approach to integrate different classes of methods from the field of dependability into the aforementioned design methodology. Most important process modules of the guideline – requirement analysis, system design, domain-specific design, and system integration – are extended by typical methods like failure mode and effect analysis or risk analysis.

The structure of the paper is as follows: We start with main results of the survey. Then we describe the resulting “design for dependability, before we conclude the paper.

2 Results of an Industry Survey

Companies counteract differently to aforementioned risk of poor dependability. The spectrum of reactions starts with “no reaction” and finishes in “a complete own process for dependability”. The survey on the application of dependability oriented design methods should give a better understanding of the present state and future needs of dealing with methods from this field. In addition to the results of the survey, the organizational framework and some conclusions are discussed in this section.

2.1 Organizational Framework

The survey was made in companies which participate in two German working groups consisting of members from industry and universities. They are shortly introduced in the following:

- The technical committee 4.15 “Mechatronics” is part of the German VDI/VDE society for measurement and automatic control. VDI and VDE are associations for German engineers and represent both, engineers within the profession and in the public area. The society for measurement and automatic control is one in twenty technical divisions. Each consists of different technical committees like the subject matter: the technical committee 4.15 “Mechatronics”. Most companies in this network are big-sized businesses.
- The innovation network “OWL-Maschinenbau” is a regional working group. Participants are companies and universities from a smaller part of Germany which is called “Ostwestfalen”. This is a part of the federal state North Rhine-Westphalia. Most companies in this network are small and medium-sized businesses.

The used survey method was an online-questionnaire with eleven different questions. Companies of aforementioned working groups were asked to support the survey by an email invitation. Reasons for the choice of this type were low costs, high number of addressees, and fast answers.

2.2 Main Results

In the following, main results of the survey are presented. 21 companies participate. Their business sizes differ as well as their types of products. Exemplary industries are automotive, electronic or plant engineering. Research and development projects are in the focus of these companies as well as products in the production phase.

The results regarding to the present state on the application of dependability oriented design methods can be structured in

- types of applied methods
- application time in the design process
- character and reason of application

Failure mode and effect analyses, checklists, and hazard analyses are most applied methods in the participating companies of the survey. All companies apply at least one of these methods. The detailed numbers of answers are shown in the following table.

Tab. 1: Types and numbers of applied methods

Method	Applying companies* [# answers]	Percentage** [%]
Failure mode and effect analysis	13	68
Preliminary hazard analysis	1	5
Functional hazard assessment	7	37
Hazard analysis	8	42
Fault tree analysis	6	32
Software deviation analysis	1	5
Monte Carlo simulation	1	5
Checklist	13	68

* 19 of 21 companies answer this question. More than one answer is allowed.
** 19 answers are equivalent to 100%.

Furthermore another finding could be identified: The most applied methods are the most generic, too. The failure mode and effect analysis, the hazard analysis and the checklist could be used for all kinds of projects, products and processes. They could be representative for different classes of dependability oriented design methods.

Other results of the survey concern the application time of these methods in the design process. Typical answers were either “in the conceptual design phase” or “in the phase where the product is actually finished already”. More than 50% answer in this way. Only 3 of 20 companies answer that they apply these methods continuous to the design process. In another question, 3 of 19 companies answer that they have an own continuous process for dependability.

Last important result regarding to the present state are the different characters of the applications and the reasons for them. More than 75% of the companies comprehend the evidence as most important benefit of these methods and more than half the companies approve the systematic way of these methods. The main idea of these methods, to improve the design by identifying poor aspects, is not chosen as much. Only one third of the companies agree with this meaning.

The results regarding to the future needs on the application of dependability oriented design methods can be structured in

- general forecast of future applications
- deficits of actual methods
- special research and development needs in the field of dependability

The general question for the prognosis of future applications shows a clear trend: 16 of 21 companies forecast an increasing application behavior. The remaining 5 companies assume that it will be constant in the future. Frequent named reasons were an “increasing complexity of mechatronic systems” and “increasing legal requirements”. This result includes that there must be potentials to increase the applications. To investigate these potentials the next main result shows answers for the question of deficits of actual methods. Most named deficits were “strong subject to expert knowledge”, “high efforts and costs”, and “low acceptance”. Answers for the question of special research and development needs in the field of dependability were mostly “integration and simplification of methods” and “preparation of statistical data”.

2.3 Conclusion from Survey Results

The conclusion from the survey results bases on the one hand on not used potentials and deficits in the present state. On the other hand it bases on forecast and identified needs of future application behavior.

The forecast of increasing applications of dependability oriented design methods shows in a very general way that there “must be done something” in this field. Also the named deficits support this assertion. The answer to the question “what could be done?” can be given by the unused potentials that could be identified in the survey: Dependability oriented design methods could be used continuously during the design process, they should be integrated in the design process, and they should cooperate with themselves in terms of an own dependability process. In spite of numerous existing methods, or methods that are actual in the research phase, the preferred methods for such a process should be general, simple to apply, and well known for good acceptance.

3 Dependability Oriented Design Methodology

Adapted from aforementioned results and conclusions, the approach of a dependability oriented design methodology is presented in the following. It is suggested to widen the scope of design guidelines, like e.g. VDI 2206 “Design methodology for mechatronic systems” by taking dependability into account. Similar approaches by (Storey 1996), (Knepper 2000), (Benz 2004) or (Isermann 2006) exist, but most of them are designed for special industries or do not use design methodologies as a framework that could be extended.

Our approach integrates different classes of methods, based on the findings of the survey into the design methodology for mechatronic systems. Most important process modules of the classical design methodology – requirement analysis, system design, domain-specific design, and system integration – are extended by dependability oriented process modules and classes of methods from this field.

The VDI guideline 2206 is shortly introduced, before the new approach of a “design for dependability”, including the resulting process modules, will be presented in detail. Individual parts from the dependability oriented design methodology have been already applied on a research project called “Railcab” (Walther et al. 2006).

3.1 VDI Guideline 2206 “Design Methodology for Mechatronic Systems”

The VDI guideline 2206 on “Design methodology for mechatronic systems” deals with the development of a modern mechatronic product in its entirety. In this way it creates an essential basis for the communication and cooperation of experts in the disciplines involved. The guideline, published by the association of German engineers in 2004, promotes interdisciplinary cooperation, which has proven to be an outstanding factor in the success of the development of mechatronic systems.

The systematic procedure for the design of mechatronic systems can be described by a V-model. It starts with requirements, and it results in the product. Basic elements inside the V-model are system design, domain-specific design, system integration, assurance of properties, and modeling with model analysis. The logical order of these elements is shown in the figure below. Especially the assurance of properties points up the benefit of the V-shape: requirements and specifications from the system design can be verified and validated in different steps of the system integration (VDI 2004).

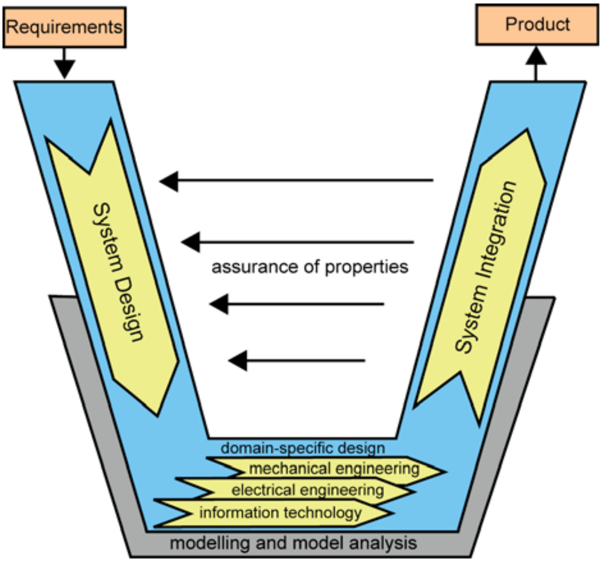

Fig. 1: V-model for the design of mechatronic systems (VDI 2004)

3.2 Design for Dependability

The "Design for dependability" bases on aforementioned procedure. The V-model is extended by another V, which takes aspects of dependability into account to the design methodology for mechatronic systems (Müller and Wallaschek 2006).

In detail the system design is extended by the different process modules:

- requirement analysis of dependability
- failure-, hazard- and risk analyses
- conceptual design for dependability
- dependability analyses of cooperation and integration

These process modules are interlocked and result in a macro-cycle. This macro-cycle is on the one hand a complete dependability process for its own, on the other it is collaborating with the components of the classical design methodology.

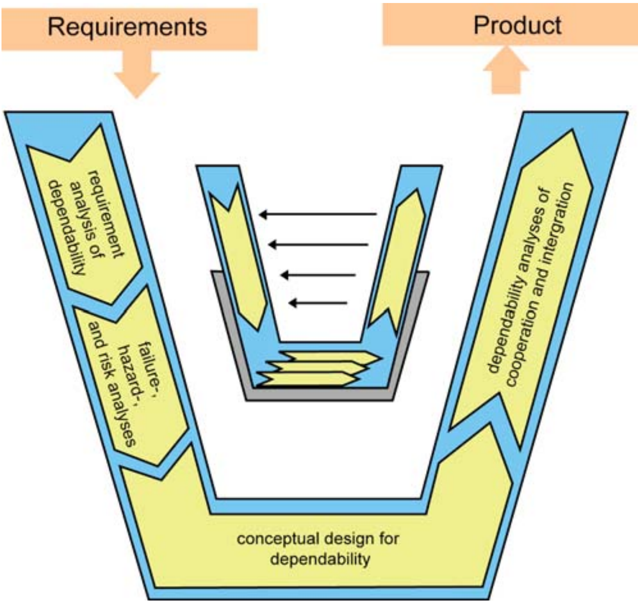

Fig. 2: Macro-cycle of the “Design for dependability”

3.3 Process Modules

The process modules from the macro-cycle of the “Design for dependability” are explained in-depth in the next sections. Inputs, tasks and results are presented. Furthermore, their collaboration is shown with the classical V-model. Recommended methods or classes of them conclude the characterization of the process modules.

Requirement Analysis of Dependability

This process module includes the task of identifying requirements of dependability. Typical inputs are classical requirement list, general design task, functional structure, checklists, guidelines, standards, and customer needs. These inputs have to be analyzed for requirements of dependability. Qualitative and quantitative requirements are possible results; e.g. a value for reliability or the demand of achieving a safe-state in predefined situations. The classical requirement list, the general design task, and the functional structure are explicit connections to the classical design methodology.

In addition to the analyses of these inputs, creativity methods are recommended methods to identify requirements. A proposed method to document these findings of dependability requirements could be a checklist. The later product will be assessed against it and future developments can re-use it. The method "checklist" is a well known and frequently applied instrument as shown in the results of the survey.

Failure-, Hazard-, and Risk Analyses

Most substantial process module of the macro-cycle includes failure-, hazards-, and risk analyses. These three analyses represent different classes of methods that should be applied in the mentioned order. Inputs of this module can be different levels of results from the system design phase of the classical design methodology: general design task, function structure, and solution concepts. Independent of the used level, the tasks of this phase are:

- identifying of weak spots
  – failure analyses
- analyzing of failure; deducting and identifying of consequences
  – hazard analyses
- assessing of consequences
  – risk analyses

The results of these tasks are assessed possibilities of consequences that based on possible failures or other identified hazards.

Recommended methods of these classes are the well-established failure mode and effect analysis (failure analysis), the functional hazard analysis and the risk matrix.

Conceptual Design for Dependability

The "conceptual design for dependability" bases on the theory of general concepts for dependability (Müller and Wallaschek 2006). These general concepts represent the root of the matter for different solutions in this field; they often base on the same idea.

According to the cause-and-effect chain for faults (Laprie 1992) the general concepts for dependability can be structured by the alternatives to stop fault expansion:

- fault prevention – to prevent the real cause
- fault/error monitoring – to detect an fault/error, diagnose and realize first counteractive measures
- fault tolerance – to operate the system with all functionalities instead of fault/error occurrence

The applying of these concepts to find specific solutions is the task of this process module. Concepts to cope with the input of identified and assessed risks (result of the process module before) have to be found, transferred and implemented.

Analyses of Cooperation and Integration

During the integration phase of the classical design methodology a correct cooperation and the prevention of incompatibilities have to be assured. Inputs of this process module are sub-systems that fulfill the requirements. The result is an overall system or further step of a sub-system that fulfill the requirements, too. Thus, the task of this process module is to analyze cooperation and integration of sub-systems and the overall system. Methods for testing, verification and validation are recommended for this phase as well as the application of the checklist from the requirement analysis of dependability.

4 Conclusion

Increasing functionality of mechatronic systems represent both, threat and potential for dependability. The growing risk of poor dependability for these systems is one effect. Companies counteract differently to this challenge.

The paper presented results of an industry survey on the application of dependability oriented design methods. An increasing application of these methods is forecasted. Potentials to cope with this challenge could be identified as well. Based on these most important results an approach for a “Design for dependability” is sketched. It takes aspects of different dependability analyses into account to the well-established design methodology for mechatronic systems.

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Holistic Methods in Product Development

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Abstract
When solving design problems a holistic view is often required, because an optimization of products depends on sets of sometimes contradictory goals and the properties especially of complex products are related in a likewise complex network. Another important reason for a holistic view on products can be a high integration level: e.g. cost or weight optimization needs often the realization of many different functions in the same parts or components. A short insight into important historic roots of holistic methods is given. Some different approaches for holistic methods are described, discussed and evaluated. A conclusion will be given about the future needs for holistic methods and the future possibilities to use holistic methods.

Keywords
Design Methodology, Holistic Methods, Product Development Process

1 Introduction

The perhaps most important ancestor of the methods of problem solving was René Descartes and his very famous book "Discours de la Méthode" (1681) [Citation in 1].

Since Descartes we know the general problem solving strategy:

- Clarification of the problem,
- decomposition of the problem,
- finding part solutions,
- analyzing and evaluating,
- conclusion.

The “classical” Design Methodology strongly follows this strategy [e.g. 2, 3]. These methods were surely a counter movement to the earlier holistic design processes ruled rather by an artistic approach or craftsmanship than by the scientific methods. Basis of earlier design methods were generally previous solutions and a local variation or adaption of structures and/or properties.

In principle this old method was mainly a “Holistic Design” because the view was directed from the beginning of the process to the total product. For teaching beginners and for using computers these old methods were insufficient and so were the step by step methods a great success. Modern product development has become more and more a highly complicated process having to meet a large number of different goals and conditions.

Because the goals, conditions and the structural properties of the products are highly interrelated, it is impossible to find an optimum for the whole product as a kind of sum or product of single optima. A very simple example shows the problem: The choice of a cheap material for a screw of the connecting roads of a combustion motor effects a more expensive motor, because the casing have to be larger and for high stiffness it has to be heavier and more expensive. Especially in the case of contradictory goals – always related to a special solution – methods are required to find, to evaluate and to optimize the solutions sometimes in a holistic way.

2 Historic Roots for Holistic Methods

The old Greeks had a saying “The Whole is more than the Sum of the Parts”. Especially for modern complex products we should remember this important truth.

An early approach for a holistic model of the design process gave 1941 Wögerbauer [4], see Fig. 1.

Franke [5] in 1976 gave a modern interpretation of Wögerbauers diagram as a model of a highly complicated simultaneous equation system with the following features:

- The parameters have different characters: Vectors, tensors, general mathematical structures (e.g. graphs, set systems) with definite, stochastic or/and time dependent values.
- The relations are only partly known, sometimes heuristic, logically or mathematically.
- Normally there is no solver for the whole system.

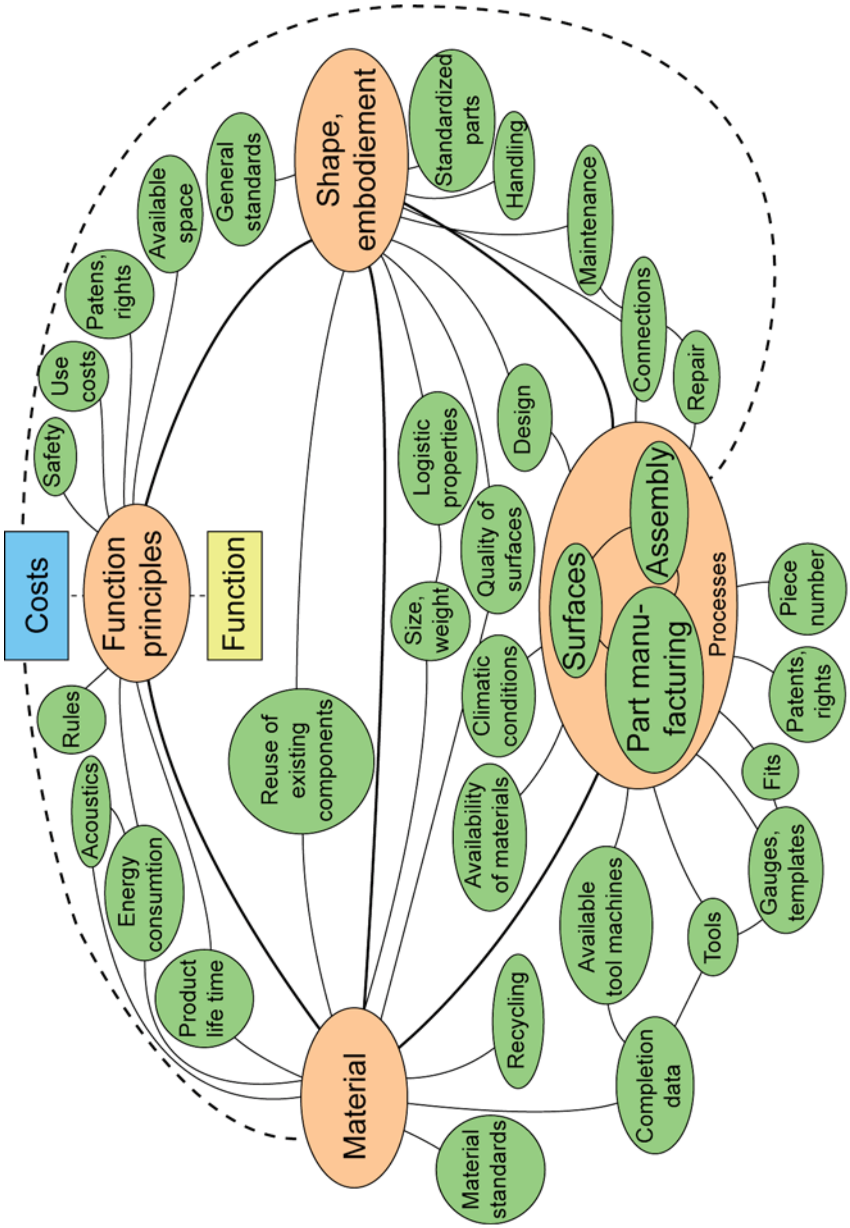


Fig. 1: Wögerbauers holistic model of design (1941)

The practical way to solve such a system is first to assume some solving parameters and/or structures and then to solve parts of the system, and thereafter enlarge the solving area iteratively up to a total solution.

It follows that a good designer needs experience and heuristic strategies for a successful solving process.

A general attempt for a systematic way to choice the right directions for the solving process in Wögerbauers sy stem was made by the author in Fig. 2.

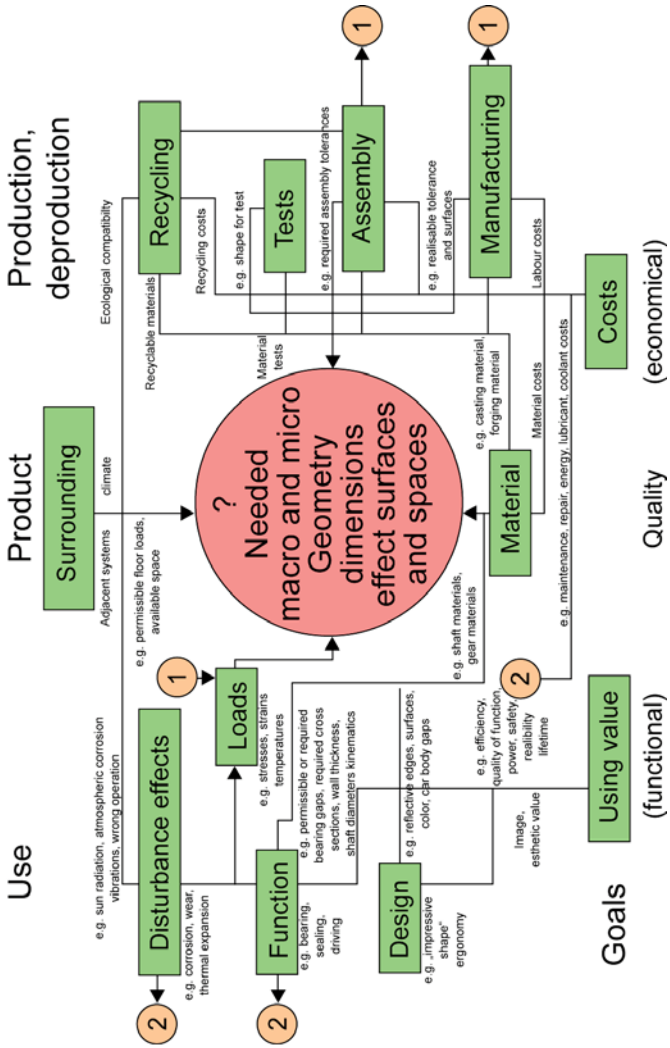


Fig. 2: Authors proposal for a general strategical order of Wögerbauers system for optimizing functional and economical goals under the different conditions of use and production of a product

In case of well known products this general system can be concretely realized as will be shown later.

3 Some Holistic Approaches to the Design Process

3.1 Catalogues

The simplest approach to a holistic design is the selection of a total product or a complex component from a catalogue. It is a standard method for finding optimal machine elements.

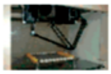
Bauform	Freiheits grad	Bezeichnung	Bild	Hersteller	Herstelleradresse
Delta	3	IRB 340 Flexpicker		ABB AG	Gottlieb-Daimler-Str. 8; D-68165 Mannheim; Tel.: +49 (0)621 4381 0
Delta	3	Speed-R-Man		Centre d'Etudes et de Recherches de Toulouse	2. avenue Edouard Belin, BP 4025; 31055 Toulouse CEDEX 4 - France; Tel.: (33) 05 62 25 25 60
Delta	3	Delta		DEMAUREX S.A.	Chemin des Mesanges 3; CH-1032 Romanel; S/Lausanne; Schweiz
Delta	3	MicroDelta 240		DMT-EPFL	Groupe de Robotique Parallele; Institut des Systems Robotiques; CH - 1015 Lausanne
Delta	3	Delta 720		DMT-EPFL	Groupe de Robotique Parallele; Institut des Systems Robotiques; CH - 1015 Lausanne

Fig. 3: Part of a systematic catalogue of parallel robots [7]

With so called “Konstruktionskatalogen” (design catalogues) [3, 6] it is possible to find also solutions for relatively higher complicated systems. A condition for such catalogues is a morphological systematized collection of solutions and their characteristic properties.

The morphological structure helps to find the complete set of possible solutions. Typical properties for the spanning morphological tree (or matrix) are qualitative, integer numbered or structural. An example from a collaborative research center “Parallel Roboter” in Braunschweig, Germany shows Fig. 3.

3.2 Total Properties and Complex Principles

Many very important properties of products or components are related to an entire product or an entire complex component, e.g. a car body. Examples are: Vibration behavior, stiffness, total inertia, life cycle costs, reliability, safety a.s.o.

Often we find good solutions only by the selection of complex principles or structures. Simple examples are the selection of a radial split casing for high stiffness or the selection of a parallel circuit for high reliability.

Sometimes we can calculate such total properties by a general algebraic approach [5] based on the circuit structure. Fig. 4 shows an example for a specially structured circuit. By such means relatively general catalogues of optimal structures and circuits can be found. The circuit structures generally define an algebraic system for calculating total values. Different properties need different mathematical operations for a concrete realizing of the general algebraic formulas.

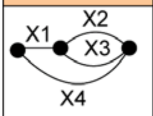
Circuit structure	General algebraic formular	Special formula for a spring structure (spring rate)	Special formula for reliablity
	X1(X2+X3)+X4	1/(1/C1+1/(C2+C3))+C4	(1-P1(1-P2)(1-P3)(1-P4))

Fig. 4: Total values of different properties can be calculated by generally algebraic formulas given by circuit topology

3.3 Intuitive Systems of Relations

A good help in the first phases of design, especially for an early analysis of contradictions between wanted goals and properties and given conditions can be a first mind map as a collection of parameters and their relations. Fig. 5 shows as an example a mind map for a personal car.

In 1976 the author proposed to model the relations in a so called “Relevanz Matrix” (Matrix of evaluated relations), where the level of correlations was estimated by numbers [5].

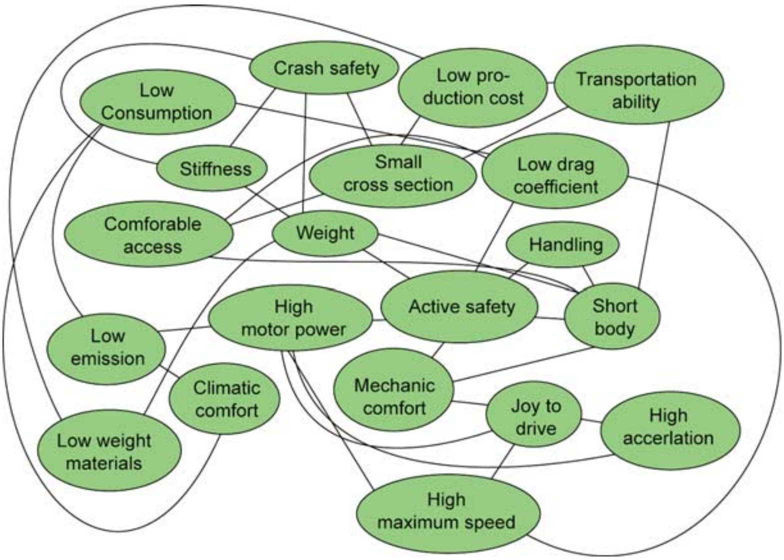
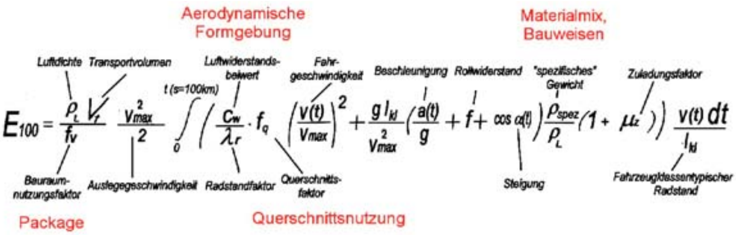


Fig. 5: Part of a mind map of the relations between important parameters of a car (extremely simplified)

Such a mind map can help to find and to define the correct correlations between the parameters, e.g. direct positive or negative (or neutral) correlations or even exact mathematical functions. So in case of a car relations between weight, drag coefficients, cross sections, speed, acceleration and consumption can be found as shown in formula (1):



(1)

Similar relations can be found for stiffness, handling and other parameters. In earlier papers the author proposed to structure such mind maps in a defined order in a specially arranged table, that the goals and the requirements are arranged at the left side, the structural and material parameters (selectable and variable design parameters) are arranged at the right side. The middle area shows the known relations between the goals and requirements and the design parameters. Fig. 6 shows an example for a simple cylindrical pressure vessel (two plane covers and one shell ring):

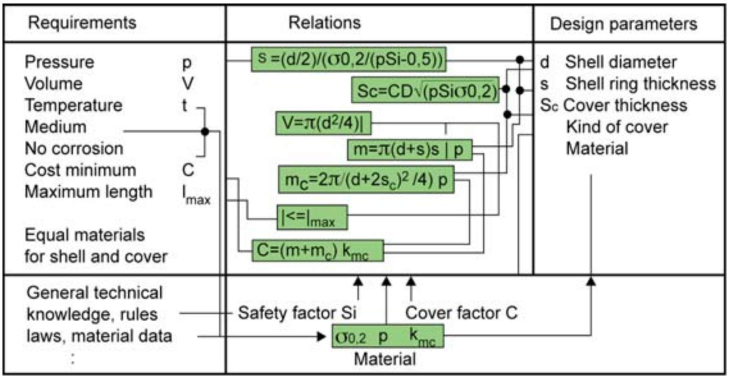


Fig. 6: A systematic design oriented network of relations for a simple pressure vessel

In simple cases as shown it is possible to solve the system mathematically e.g. under minimum conditions. Normally there are no simple mathematical solutions. But even in this case a problem modeling in the described manner **can be extremely helpful to find strategies for solving** under contradictory requirements.

4 Algorithmic Holistic Solving Procedures

Well known products can be modeled by algorithms. In this case many known relations exist between functional, economical and structural parameters. Experienced designers know strategies for an optimal iterative definition of the design parameters. A practically used example shows Fig. 7. Nearly 600 simultaneous equations were used for an optimization of high pressure centrifugal pumps. An experienced designer knows the most important design parameters: Driving speed and the number of stages.

The same program is also able to optimize with regard to robustness (short shafts) or stability of head-flow-characteristic.

Predefined different shapes of impellers and diffusers can be analyzed.

The general disadvantage of such approaches is the relatively narrow validity, the high necessary expense and the necessary expertise for programming, the advantage is an extremely high level of quantitative information.

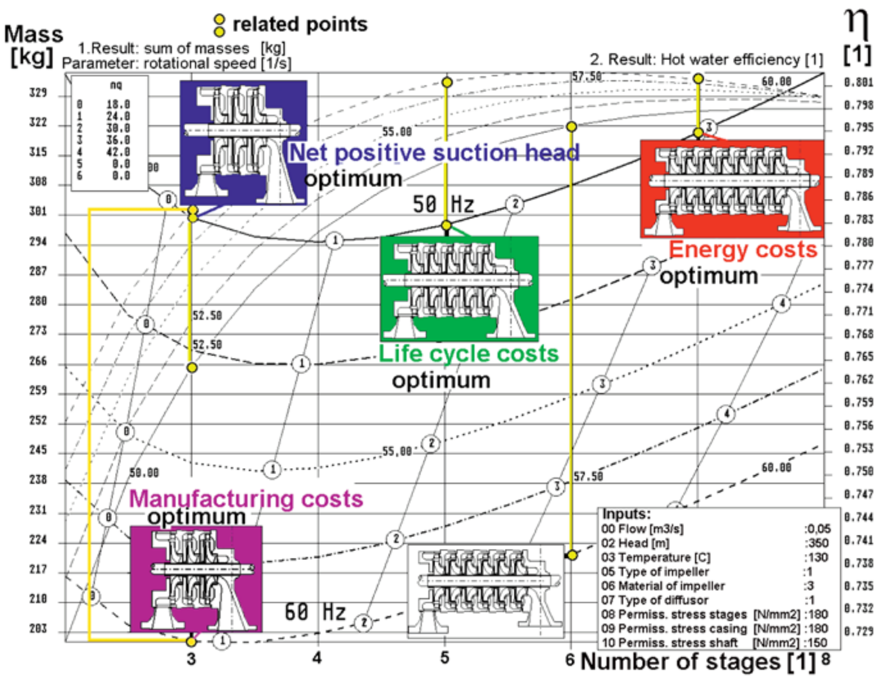


Fig. 7: Algorithmic optimization of a complete centrifugal pump related to 3 different goals: Low energy consumption, low manufacturing costs (labor costs), low material costs (related to the weight) and a low net positive suction head) for a defined flow and a defined pump head (pressure)

5 Constraint Systems

The modern CAD-systems have in many cases integrated constraint solvers and can associate physical properties with the geometry. By this means not to complicated products can be totally modeled. For some defined requirements and conditions such a system can automatically find a requirement adapted optimized solution. A constraint based system was proposed by Brey, Fig. 8. He validated the usefulness at the example of pressure vessels, Fig. 9.

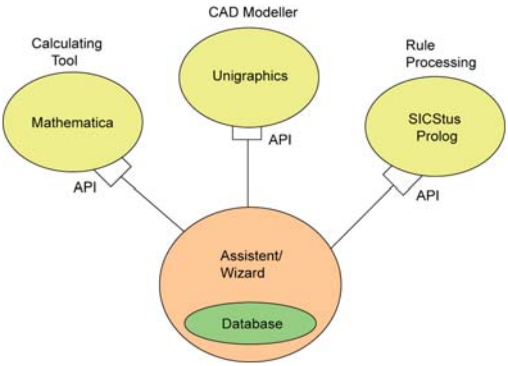


Fig. 8: Architecture of a constraint based design system of Brey [8]

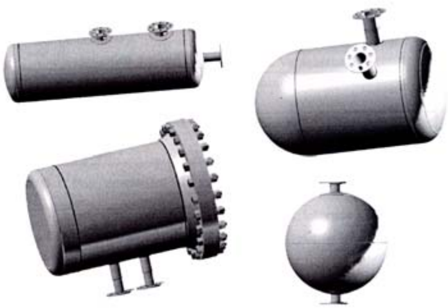


Fig. 9: Some configurations of pressure vessels generated by Breys system

6 Neuronal Networks

Neuronal networks allow to find a total set of optimal parameters of a design regarding given goals and conditions. The training of such a network needs much experience with the product and very good known optimal solutions. For mechanical design (gear boxes) has F.L. Krause [9] discussed the ability of this method to optimize parameters of a generally known design.

7 Conclusions and Acknowledgements

The need of additional holistic methods was described. Some available methods were discussed and the advantages and disadvantages were evaluated.

Especially the optimization of complex products needs the view on the total product and an early insight to possible contradictions of the different goals.

The use of computers increases the future abilities for modeling complex views on the total products. It remains the general problem that a total view needs a relatively exact knowledge of the wanted product.

Nevertheless gave holistic methods as catalogues or the knowledge of complex principles ideas for solutions in early stages of design. The author thanks the Deutsche Forschungsgemeinschaft (DFG) for financing the research in the collaborative research centers SFB 516 and SFB 562.

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A Holistic Approach for Integrated Requirements Modeling in the Product Development Process

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Abstract
Product development is becoming more and more complex. As a consequence of the increasing product complexity and the involvement of multi-disciplinary supply chains in product development, the modeling of requirements has become a highly significant part of the product development process. Requirements are often isolated and limited to certain development stages. A solution is the continuous integration of requirements into the product development process. This paper provides a concept for the consistent modeling of requirements in the product development process.

Keywords
Requirements Modeling, Product Lifecycle Management, Integration, Product Development Process

1 Introduction

A requirement is a statement identifying a capability, physical characteristic, or quality factor that bounds a product or process need for which a solution will be pursued [1]. Time to market, product complexity, collaborative teamwork, distributed development and cost reduction have accentuated the impact of requirements modeling on product development. The topic itself is not new and has been successfully used in the fields of system and software development. Studies have shown that requirements' modeling is a major success factor in the execution of such products [2].

Today, requirements' modeling applied to traditional product development is in its infancy. Several software solutions are available; however they have specific scopes. A major shortcoming of these tools is that they are mainly stand alone solutions and cannot be suitably integrated in the development process. The integration to PDM/PLM, ERP and Manufacturing related software is an aspect that is not in the focus of most tools. Therefore, only a tight integration with all disciplines of product development, the supply chain as well as the product development process guarantee a successful implementation of requirements modeling in product development.

2 The Requirements Modeling Process

The traditional requirements modeling process has been summarized by Nuseibeh [3]. However, the described process approaches requirements modeling from a system or software engineering point of view.

The requirements modeling process explained in figure 1 is based on the traditional process but has been adapted to match the focused approach of product development.

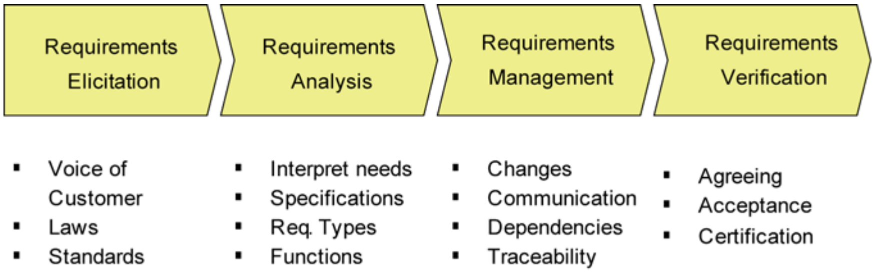

Fig. 1: Requirements Modeling Process

The first step is the elicitation of requirements. Several methods, including interviews and market analysis, have been developed to elicit requirements. This paper assumes that these practices have been undertaken and that the voice of the customer is stated in requirements specification documents.

During the analysis phase requirements may need to be interpreted and translated into a form that is suitable for an engineer. This is an important task and therefore needs involvement of all stakeholders of the product development project (marketing, customer, engineering, production etc.).

Requirements change and evolve during the product development lifecycle. These changes need to be tracked and traced. Most traditional requirements management tools, e.g. DOORS [4] promise to offer sufficient support in this field.

The fulfillment of requirements needs to be validated with virtual and/or physical tests. A product is deemed successful (by means of satisfying the customer) if all requirements are fulfilled.

Requirements' modeling takes place in all phases of product development. Only a few processes (e.g. change management) have such a broad scope or the ability to influence all other aspects and phases of the product to be developed.

More emphasis needs to be put on later development phases such as e.g. usage, maintenance and recycling. The knowledge gained in these phases, once included in the development process, can accelerate the development of new products. Lessons learned and frontloading [5] are suitable methods for this knowledge transfer.

3 Concept for Integrated Requirements Modeling

Integrated requirements' modeling is a consistent concept allowing the continuous integration of requirements into every lifecycle phase of product development. Starting with the requirements specification document, an ontology for requirements is the basis for classification and traceability.

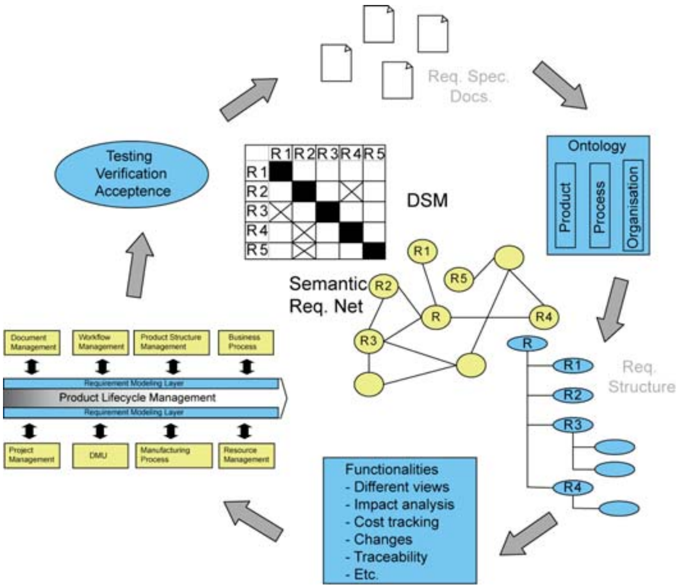

Fig. 2: Integrated Requirements Modeling

Figure 2 illustrates the concept of integrated requirements modeling with the different aspects taken into consideration. These different aspects are explained in detail in the following sections.

3.1 Ontology Based Gathering of Requirements

Requirements specification documents are very comprehensive by their nature. For a car interior it may contain some 70 features with an average 50 pages of specifications each [6]. The gathering of relevant information may be best performed with the help of automated support for the filtering and classification of such documents. State of the art methods such as the *Axiomatic Theory of Design* [7] or *linguistic methods* [8] are capable of handling the required actions.

An ontology is a formal description of objects and their properties, relationships, constraints, and behaviors [9]. The requirements types and classes defined are the core of the ontology. Specific views can be derived and represented in hierarchical form. In the following the specific occurrence of types are explained.

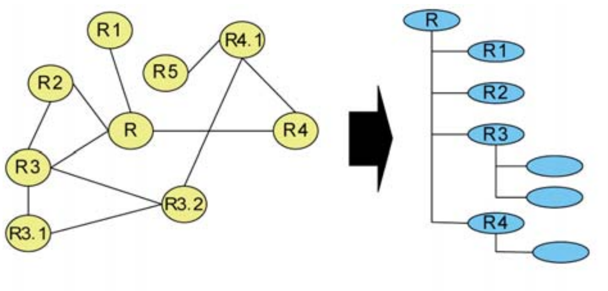

Fig. 3: Deriving Structures from a Semantic Requirements Net

Product requirements are the most comprehensive requirements type. As mentioned previously, a product has to fulfill many requirements originating from many different sources. However, all these requirements are directly related to the product to be developed.

Process requirements are related to manufacturing processes or to demands concerning business processes. Furthermore they can be related to support processes.

Organizational requirements define project related issues and other formal requirements. They are not directly related to the other requirement types; however in complex development environments such details need to be integrated in the product development process as well. Examples of organizational requirements are related to project and data management, documentation, reporting etc.

A breakdown of requirements into different classes with certain attributes is the basis for constraint solving mechanisms. A constraint is a logical relation between attributes, depending on the requirements type and class.

3.2 Changing and Evolving Requirements / Traceability

During product development, requirements are undergoing a constant evolutionary process of modification and improvement. It is of essential importance to be able to follow the lifecycle of a requirement – i.e. from its origins, through its development and specification, to its subsequent deployment and use, and through periods of on-going refinement and iteration in any of these phases as well as its integration aspects - and provide rollback options to certain development stages.

Different requirement types have different dependencies. Through the refinement of the product requirements the dependencies can be traced forward and backward in a consistent manner. For quantitative product requirements, physical relations in the form of mathematical equations (constraints) can be defined and solved with constraint solvers [8].

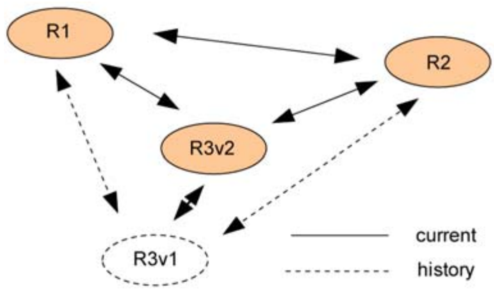

Fig. 4: Requirements Traceability and Evolution

The concept of requirements traceability is the most efficient manner of linking the various concepts included in requirements modeling. Simply put, requirements traceability refers to the ability to describe and follow the lifecycle of a requirement in both a forward and backward direction. All possible dependencies must be defined between requirements. The dependencies can be seen as entities in their own right. As such, they may possess attributes specific to each link (see figure 4).

3.3 Representation

Requirements are often decomposed into sub-requirements. Although a well conceived classification reduces some of the complexity of requirements, the representation and the dependencies between requirements are still complex. Matrices (e.g. *DSM - Design Structure Matrix*) are suitable structures where one may enter and process such information but, due to the large amount of information, the representation rapidly reaches an unmanageable scope. A *semantic net* is seen as a solution to represent requirements and their dependencies with appropriate filter options.

4 Integration Model for Product Requirements

A functional requirement contains a statement on what the product to be developed must do. Non functional requirements contain statements on properties or qualities the product must have [10]. Different customers may state their requirements in different ways and use different vocabularies for the same things. In times of technical and social changes and ever changing environments, function orientation provides the necessary flexibility for a company. Functions which fulfill requirements are profitable in the long term and remain stable as opposed to requirements which can change quickly [11]. Function orientation also provides the ability for cross domain collaboration. Through the additional function layer the different requirements can be linked to an internal functional structure that represents the goals that have to be fulfilled and that can be verified.

Functions can be linked with specific processes. The technical realization of functions takes place in these processes. Furthermore, functions can also be related to specific positions in the product structure.

As a result of linking the requirements with functions, functions to processes and the product structure, an indirect relation between requirements, processes and the product structure has been established (see figure 5). The impact of a modification on a requirement can be traced to specific positions in the product structure and to related processes.

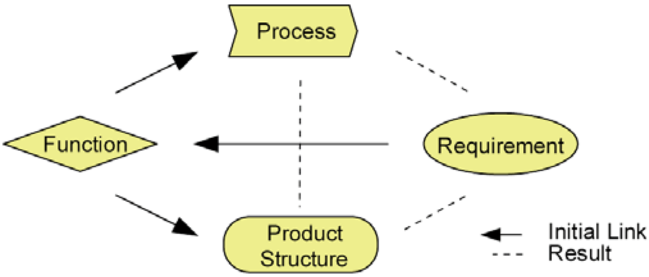

Fig. 5: Model for Integrated Functional Product Requirements

5 Process Integration Model

Processes can be of different nature (see figure 6). They can be divided into core and support processes which are major aspects of a holistic integrated requirements modeling concept [12]. Core processes are value adding processes. The two main core process categories are business processes (in product development mostly related to engineering processes) and manufacturing processes. As a basis for program/project and resource management integration, they contain information about cost, time and resources.

They can also serve as a basis for the relation from requirements to the corresponding process steps and therefore to the project timeline or lifecycle stage of the product. Furthermore, specific customer and supplier processes can be integrated and taken into consideration for a holistic approach of product development. Thus integration with process modeling tools is an important issue.

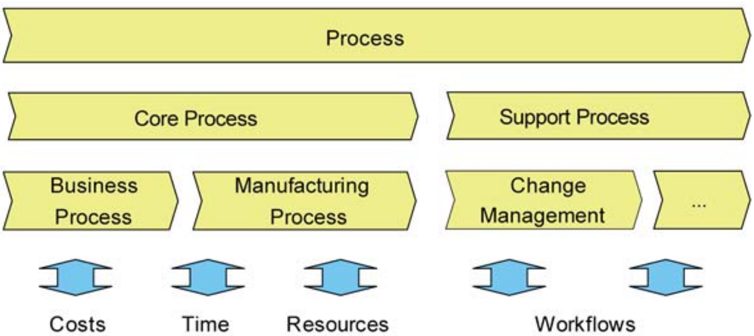

Fig. 6: Integration of Requirements to Processes

Support processes are necessary in a heterogeneous development environment in order to provide the necessary support and infrastructure for the development program. Examples of support processes are change or escalation management. Support processes are the result of actions originating from certain workflows. Thus, the best way to achieve integration with workflow management is through integration with support processes.

6 Integration of Product Structure

The product structure, defined briefly as a decomposition of the whole product into administrable objects, is mostly geometry centric in current applications. Product structuring describes the manner in which objects are arranged to form a product. These objects are managed in PDM systems, where they are viewed as central data building blocks capable of describing structures from the part level upwards. Mapping requirement structures to product structures, updating requirement structures, linking other structures such as manufacturing or functional views of a product can lead to an arduous manual process. A concept was introduced by Klaar [13] where he suggests the linking of requirements to components in the appropriate CAD application. Since this is only possible for certain requirement types the functional approach suggested here offers more flexibility hereby.

Figure 7 shows a model depicting the integration of requirements modeling into a universal product structure. The goal is to enhance this model and integrate it into the whole product development process.

As a result of a parallelization of activities in the product development process it has to be expected that, during the product structure design, not all requirements are adequately specified. It is common that new requirements could be defined during this process, or existing ones be modified.

Hence it is necessary to have a superior concept capable of collecting a variety of engineering information and providing the lifecycle processes with consistent product data information. The universal product structure, which can serve as a central information pool, is such a concept. All relevant structures, including the requirements net, functional net etc. are derived dynamically and linked bidirectional with the universal product structure. These structures can consist of general terms (i.e. placeholders) which serve as universal carriers of information.

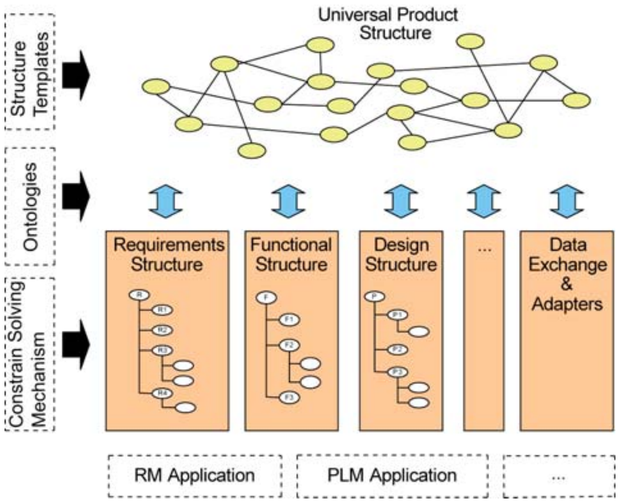

Fig. 7: Product Structure Integration

7 IT-System Integration Aspects

The major benefit of requirements modeling lies in the seamless integration with other fields of product development. This is done by bringing requirements modeling in direct correlation with PLM systems and other software tools used in product development.

For an efficient product development strategy, requirements must be integrated with the fields shown in figure 8.

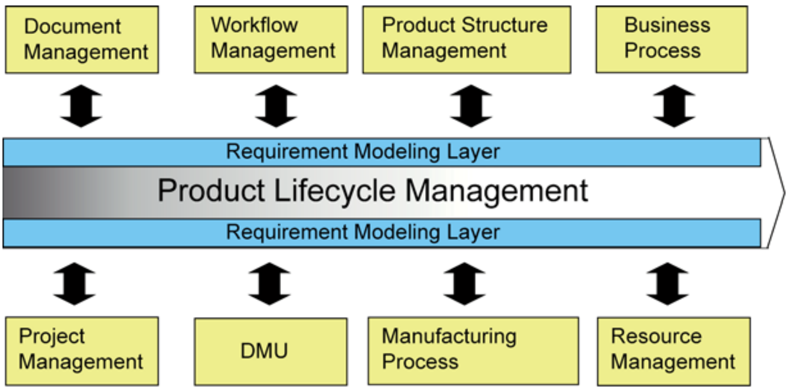

Fig. 8: Requirements Modeling in the PLM Context

Communications generated between requirements modeling and the other fields of product development allow a smoother development flow between the various phases of product development in a more structured manner and ensure that a product is developed following fully documented state of the art procedures. All of this considerably accelerates development time and ensures that the product satisfies all customer requirements beyond current standards.

9 Summary and Outlook

This paper provides a holistic approach to requirements modeling in which requirements are fully integrated with the product development process. Unlike classical product development, the inclusion of requirements modeling at every stage during product development is proposed. This also allows an easier integration of customer and supplier processes.

Ongoing research activities include the prototypical realization of the concept and the integration into a product development platform.

10 Acknowledgments

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Multi-level Representation for Supporting the Conceptual Design Phase of Modular Products

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Abstract
Designing a new product, in most cases, means a modification of an existing one. Both adopting known solutions in different products, that inserting new technological processes into a consolidated context, the most design effort must be dedicated to the early evaluation of the impact of needed engineering changes to achieve the final result, in terms of cost, quality and time. Such activity is particularly strategic in the modular product development. The aim of our research work is to develop a method and the related tools that enable designers to easily represent the product platform, to structure the relations between modules defined at different levels of detail and, hence, to simulate, analyze and evaluate the modifications impact during the new product variant definition phase. A multi-level product structure able to represent the product informative content at different levels of detail is presented.

Keywords
Modularity, Change Propagation, Conceptual Design

1 Introduction

The paradigm called *mass customization* has been recently defined; it embraces concepts such as modularity, product family, design for commonality and design for variety. The goal of *mass customisation* (Pine 1993) is to adopt new product development methodologies to offer a large variety of customized products while maintaining low costs in production and in logistics. The development of modular products is one the main possible solutions. A well-designed modular product architecture can help the management of product changes and upgrades, product variety and component standardization (O'Grady 1999). Towards this goal, modular products can be supported by conceiving *product platforms*. According to Simpson et al. (2001) a product platform can be defined as a set of parameters, features, and/or components that remain constant from product to product, within a given product family. The product platform has to provide the necessary framework for easily obtaining customized products describing the interrelationships among various solutions with respect to customer requirements, competitive information, and related implementing processes. We believe that a platform is completely defined when it is associated both to a formal schema and also to a physical schema. Several methods are reported in literature for representing a product platform (Holtta-Otto 2005), but, generally, they involve only a formal representation neglecting the product geometric contents (physical schema). In this context, the purpose of our long-term research work is the development of a computer aided conceptual design system that allows defining the product platform and managing the configuration of the new product variant on the basis of the customer requirements considering both aspects. The product platform has been thought as a structured collection of various levels of informative and knowledge contents (functions, generic modules, specific modules based on chosen solution principles, geometric shapes) interrelated by different typologies of relationships and encapsulating the design rules (i.e. dimensioning formulas).

The multi-level product representation is based on five levels as follows: the functional model, the modular configuration, the product architectures, the layout configurations and the components geometry configurations. The different levels give a progressively more detailed viewpoint of the solution, to finally achieve a three-dimensional virtual representation (CAD model) of the resulting product variant configuration. The inheritance principle is used to link the various levels of modules instances. Horizontal, into a level, relationships involving signal, material and energy flows, as reported in the systematic approach (Pahl and Beitz 1996), are used at high level; to manage modules interactions they are extended, at lower level, by horizontal and vertical, across levels, relationships that we defined *environmental* and *implementing* relationships. These relationships consist of links with the capability of transmitting the different types of knowledge required to make the module able to fit different design constraints and able to provide the right configuration once the designer has defined the general requirements. Simple geometric entities can then be used as constitutive parts for describing modules into a layout configuration, and they can be easily reused when new models have to be reconfigured.

2 Background

Many researchers have investigated the modular product architecture definition and how it can be used to support customization. The identification of a common architecture within the company product lines has been studied to manage the product portfolio (Dahmus et al. 2000). The literature describes both theories and methods to support the modularity concretization through the product platform use (Simpson 2003). Practical tools to support the implementation and their application are widely described (Ishii and Yang 2003), (Shooter et al. 2004), (Germani et al. 2005), (Germani and Mandorli 2004), (Fujita, 2002).

A product can be defined modular and configurable if, on the basis of the product platform, it is possible to accomplish a rapid and low-cost design modification that fully satisfies the customer specifications.

The product platform can be represented, at high level, as a set of functional modules that are collected to achieve a generic overall function. To satisfy the specific customer requirements (that is the specific overall function) it is necessary to construct an appropriate assembly of module instances. The generic correspondence between modules and functions has been well established (Ulrich 1995). A basic problem is the definition of rules to map the functions with the modules represented in a complex functional structure. Stone et al. (1998), for example, develops three heuristic strategies to identify possible modules. The idea has been extended to include also product family considerations (Stone et al. 2000). An important functional classification that is a useful base to support the development of research in the product architecture definition and related design systems is reported in Hirtz et al. (2001).

In our opinion, however, some issues still remain open, in particular regarding the identification of effective methodologies to integrate the non-geometric symbolic information of such models, with the geometric numerical information required for the rough and detailed description of the product shape. This integration is the essential premise to perform the analysis/synthesis cycle that is typical of the design process: functional and technological constraints are analyzed and then synthesized in order to identify a possible design solution, that involves the definition of preliminary shapes and dimensions (product layout). This geometrical information becomes part of the knowledge to be analyzed in order to perform the next synthesis step and to define a more detailed solution. The integration becomes fundamental during the configuration of a product variant, when the product model needs to be instantiated on the basis of the configuration rules that have to make reasoning on the knowledge related to the detailed definition of the product shape and dimensions.

In this last context, this paper by providing a new product platform definition and structure allows the integration between functions, configuration rules and shape representation. In order to validate the approach, a real industrial case has been studied.

3 The Multi-Level Product Representation

By observing the difficulty of representing the complexity of the product design activity and managing the variations in configuring new solutions within a product platform, our efforts have been concentrated in the creation of a meta control system to reduce a model complexity into a synthesis task. Such complexity can be automatically managed only if the product model architecture (we intend component or sub-assembly or assembly, on the basis of the product level analyzed) is known, or if it is somehow interactively definable.

Numerous definitions have been formulated about the term model. As we consider the model as a simplified scheme, which underlines the main physical and geometrical characteristics of a process in order to understand and forecast its behavior. The product platform design is equivalent to model construction. A model simplification paradigm that aims at a substantial reduction of the number of solutions to satisfy a configuration or a design problem is the *functional abstraction* as defined by Stein (2002). It makes heuristic simplifications at two spaces –behavior level and functional level– and can be applied to product platform design in order to define the different levels of meta control for the configuration of the product variant.

A multi level framework can support the formal representation (model) of the product platform. Navigating the model can be possible to control the impact that each single modification has on the final product, and to manage the product change propagations along the product architecture as one module or a component varies respectively its functional task or its behavioral and geometrical/dimensional properties or its position within the model or the manufacturing process used to realize it.

3.1 Product Platform Representation Framework

In the framework proposed a product platform is represented (figure 1) with a set of configurations, which are gradually extended from simplified structures to exact layout and geometry.

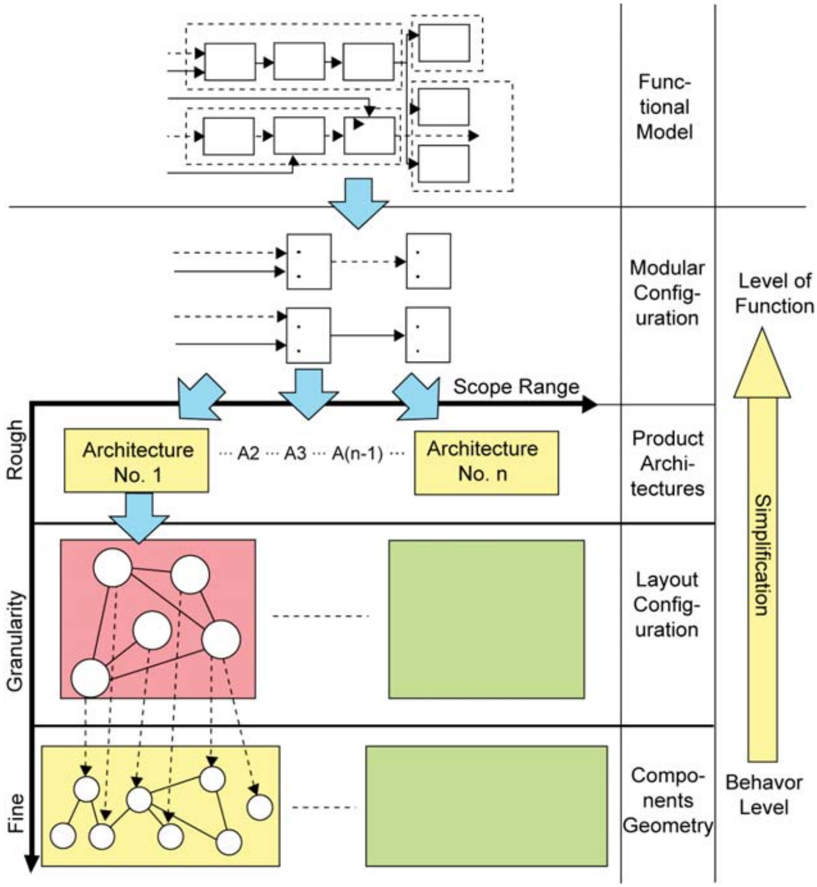

Fig. 1: The multi-level product platform framework

In order to control the design complexity and the definition of the configuration framework we adopt criteria based on granularity and range scope. A design computation is executed with each view by switching levels of granularity and width of scope range. In design process, such design view is gradually shifting from rough grain and wide scope to fine grain and narrow scope, because main layout and geometry with rough granularity restricts subsidiary layout and geometry with fine granularity. The subdivision of the product design into rough and exact product configurations allows managing the change propagation and assures the coherence of the variations within the whole product family configuration.

Functional modeling, also known as functional decomposition, is the process of breaking the overall function of a product into smaller, easily solvable sub-functions. The sub-functions are related by the flow of signal, energy and material (SEM). The most abstract product representation, in our approach, is the functional model, known as a functional structure. For each input flow the designer develops a chain of sub-functions that operate on the flow. The functional model is a combined set of functions and flows, which can be gathered together in modules. A module aims to represent a reusable standard unit, which minimizes relationships with other part of a product. The flows are internal when they connect functions belonging to the same module and external when they connect different modules. In our proposed framework we have focused on the definition of the external flows in order to manage the product design in terms of modules relationships.

The second meta level of our proposed configuration framework is represented by the modular configuration. It consists of the modules identified by the application of heuristic methods (Stone et al, 1998) to the functional model and of data flows (SEM). The modular configuration reflects the product platform modular architecture. The modular configuration is considered independent from any physical/geometrical implementation of the modules themselves.

As the modular configuration is implemented for more specific design solutions the result is a set of possible configurations of the product called product architectures (A_i). Each architecture consists of modules arrangement, of all necessary relationships between them and textual notes to completely implement the specific design solution.

In order to create a meaningful network of modules and relationships that define a specific design solution, the flows connecting modules in the first and second level are translated into both *Environmental* and *Implementing* relationships. If the whole range of possible relationships is not covered by the flows translation the designer can use additional ones to improve the product architecture representation.

The *Environmental* relationships transfer the modules semantics into rules. They embody a specific functionality of a module only at the moment it is put in the product environment (A_i). These relations are linked to the specific co-text (module functional meaning) they are related to.

The *Implementing* relationships develop the specific design solution in terms of design choices. They take into account the existing relationships among materials, raw shapes, overall dimensions, strength conditions, manufacturing processes and technological constraints of the product components.

Both *Environmental* and *Implementing* relationships represent the necessary conditions between modules to satisfy all product-leveraging requirements that are generally defined since the first conceptual design phase.

At fourth level (layout configuration) the architecture A_i is represented by a preliminary raw design that maps behavior model parts to the structure model. The designer can use a simple geometrical representation (reference planes, axis, bounding boxes, cylinders) to sketch both the functions and sub-functions contained into the modules and the relationships between them defined in the architecture configuration. At that level the relationships are translated in term of geometrical, topological and positioning constrains and parameters that can be represented with numerical values or algorithms.

At lowest level components geometry could be embodied by the digital 3D model of the product realized by using a Parametric/Feature-based CAD system where the designer defines the product shape in terms of detailed features and related parameters and constraints that developed in terms of geometry and numerical values the relationships identified in the layout configuration.

Therefore the whole product platform network is composed of the abstract level that consists of the functional model, of the modular configuration and of the product architectures that differentiate themselves from the contents of the relationships, and of the geometric/physical level that consists of the layout configuration, a geometrically translation of modules and functions into raw designs, and, finally, of the system components. It can be represented as a graph wherein each variation affects the overall structure.

3.2 Change Propagation Management

Once defined the whole product configurations (from the rough level of the modular configuration, to the fine levels of product architectures, layout and components geometry) we identify two different levels of possible design changes: the modules variation when a single module is replaced by another or some modules are aggregated and the components variation when there is a more detailed modification of the components geometry.

In the first case (figure 2) the main task is to identify which components undergo a change and how the product architecture reconfigures itself. We assume that this type of change leads to a *Product Family Innovation* due to the consistent development of the modular configuration in terms of new product functionalities and performances. The modular variations run top-down along all product configurations.

In the second case the main goal is to identify the consequent changes on the other associated components and how the product family architecture is redesigned without any changes on the modular configuration. This type of product variation, called *Rapid Product Redesign*, jumps from bottom to up and vice versa, but the change propagation is locked towards the upper meta level.

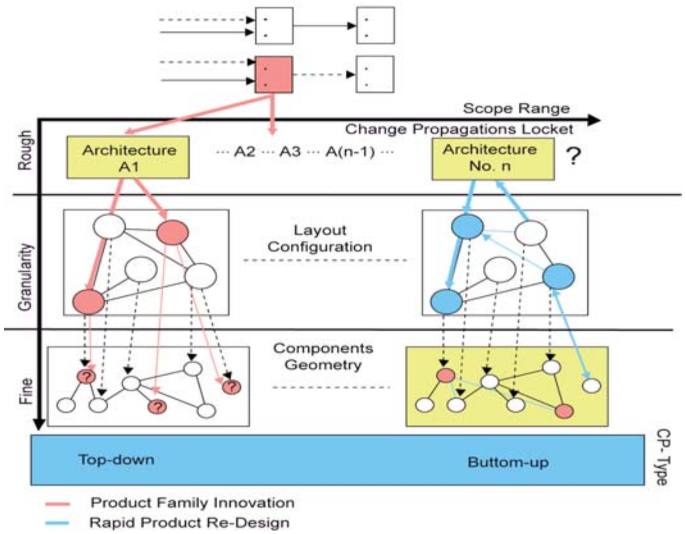

Fig. 2 Possible change propagation mechanisms

The management of this process has been set as follows. The design process can be seen as executing a series of design goals to achieve an acceptable solution. The design tasks are often defined by the industry's needs in the early design phases. The goals a modular product must achieve are related to costs, to meet the different market segments, and specific product performances etc. Based on design objectives, a set of important leveraging product requirements are listed:

- standard normative and procedures,
- market segments,
- physical principles and rules,
- product performances that are about ergonomics, product components recycling, assembly/disassembly, maintenance, etc.

Our preliminary studies on modular products show the converging attitude to this set of 4 recurring requirements. By observing the design process the requirements are often translated into relationships including constraints such as position and topology, geometry and the overall size, dimensions, physical magnitude, software specification, material, thermal and electromagnetic compatibility between connected parts.

In order to easily allow the definition of the modules relationships we have classified two different types of architecture's interface: direct and indirect. Furthermore each of them can be classified into external and internal interface. The direct interface appears when two modules are strictly related. It can be represented by several relationships of connection and coupling that are embodied by coaxial constraints, reference planes coincidence, planar alignment in the layout configuration. When two or more modules are interrelated by a third entity the interface is defined as indirect. Typical examples of entities that embody indirect interfaces are wirings, pipe systems, etc. The external interface exchanged flows of signal, energy and material with the context, while the internal interface is located within the modules network.

Leavering Requirements	Type of relationsship	Interface			
		Direct		Indirekt	
		Internal	External	Internal	External
Standard Normative and Producers	Position/Topology	R111	R211	R311	R411
	Geometry/Overall size	R112	R212	R312	R412
	Dimensons	R113	R213	R313	R413
	Material/Electromagnetic/ Thermal Combatibility	R114	R214	R314	R414
	Software Specification	R115	R215	R315	R415
	Physical magnitude	R116	R216	R316	R416
Product Performences	Position/Topology	R122	R222	R322	R422
	Geometry/Overall size	R123	R223	R323	R423
	Dimensons	R124	R224	R324	R424
	Material/Electromagnetic/ Thermal Combatibility	R125	R225	R325	R425
	Software Specification	R126	R226	R326	R426
	Physical magnitude	R127	R227	R327	R427
	Position/Topology	R131	R231	R331	R431
Market Segments	Geometry/Overall size	R132	R232	R332	R432
	Dimensons	R133	R233	R333	R433
	Material/Electromagnetic/ Thermal Combatibility	R134	R234	R334	R434
	Software Specification	R135	R235	R335	R435
	Physical magnitude	R136	R236	R336	R436
Physikal Principles and Rules	Position/Topology	R141	R241	R341	R441
	Geometry/Overall size	R142	R242	R342	R442
	Dimensons	R143	R243	R343	R443
	Material/Electromagnetic/ Thermal Combatibility	R144	R244	R344	R444
	Software Specification	R145	R245	R345	R445
	Physical magnitude	R146	R246	R346	R446

Fig. 3: The relationships database

In the figure 3 it is shown an example of relationships database for a specific product architecture that implements a well-defined product solution. Each cell is marked by a progressive alphanumeric code that represent:

$i = 1 \ldots 4$ it represents the different types of modules interface;

$j = 1 \ldots n$ it represents the different leveraging requirements that have been taken into consideration since the first design phases.

The number (n) varies according to the number of them;

k = 1…6 it represents the types of relationships that embody the leveraging requirements

For example, the relationship marked with R123 means that it is an internal direct interface (1), represents a product performance requirement (2), and is embodied by dimensional constraints (3).In order to completely implement the product architecture it is necessary to map the relationships with the modular configuration by substituting the SEM flows.

The modules matrix (figure 4, left) aims to collect the relationships from the database for each coupe of modules. For every cell the designer can map the relationships into the product architecture (figure 4, right). An applicative example is reported in the test case section.

	Module A	Module B	Module C	Module D	Module E	Module F
Module A	-	M12	M13	M14	M15	M16
Module B	-	-	M23	M24	M25	M26
Module C	-	-	-	M34	M35	M36
Module D	-	-	-	-	M45	M46
Module E	-	-	-	-	-	M56
Module F	-	-	-	-	-	-

	Relationships that Embody SEM Flows		Additional Relationships	
	Environmental	Inplementing	Environmental	Inplementing
M12	R214 R214	R425	R232	R244
M13	R312 R312	R416	R143	R434

Fig. 4: The modules matrix (left) the mapped matrix between relationships and modules (right)

4 The Test Case: the Washing Machine Configuration Process

In order to validate the approach, the configuration process has been applied on a real test case. The project has been carried out in collaboration with an Italian big industry Indesit Company that produces household appliances. In particular the product configuration approach has been experienced on washing machines. Different product lines have been analyzed to identify a common platform. The analysis has been performed according to the method proposed by Stone et al. (1998). Once defined the modular configuration the research focused on the classification of relationships among the modules to manage the design variations along the whole design process.

The washing machine example allowed testing the theoretical approach in all the various stages. The main results of the work have been reported in the following figures.

A functional analysis of the washing machine has been performed starting from a black box model. Figure 5 reports level 3 of such analysis. The functional analysis has been considered complete in order to describe the washing machine functionalities, to maintain the necessary abstraction for identifying modular configuration. In figure 5 different colors identify functions gathered in the same module.

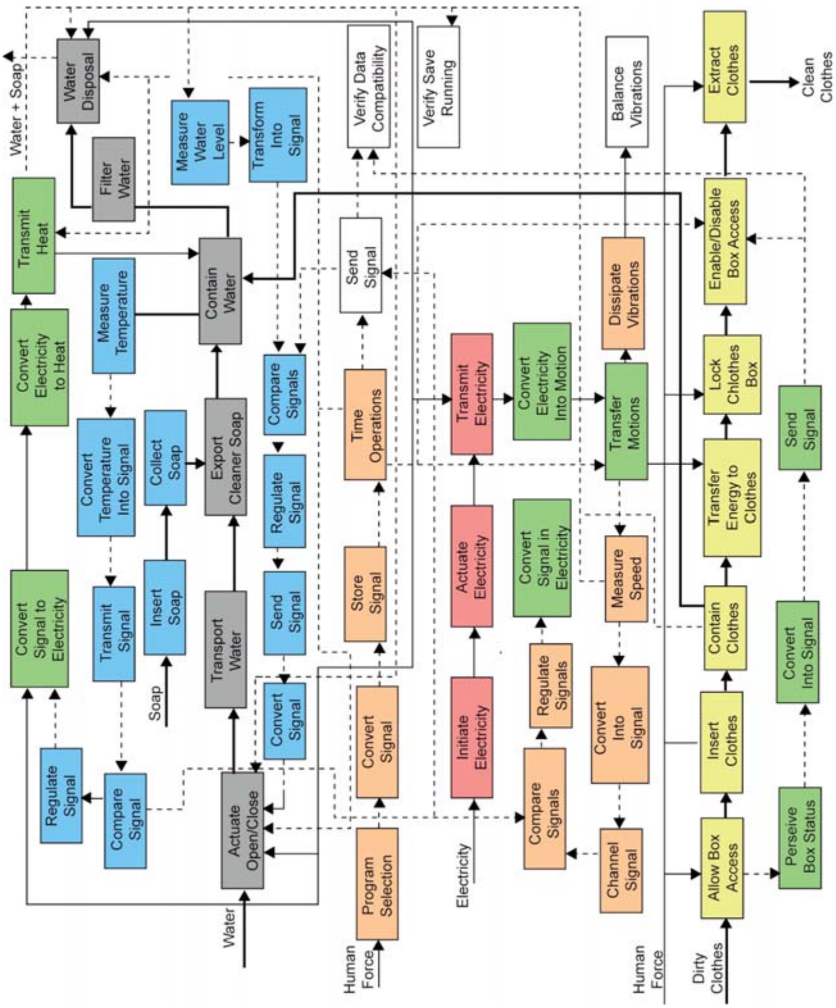

Fig. 5: The functional chain development where the modules have been identified

For instance, *clothes treatment* module has been identified by Dominant Flow methodology where the clothes constitute the main material stream. The same method has been used for *water flow*, *electricity supplier* module, etc. Conversely, *check motion parameters*, *dispatch signal*, *check unit* modules have been introduced using Branching Flow method while *motion generation* module is an example of Conversion-Transmission type.

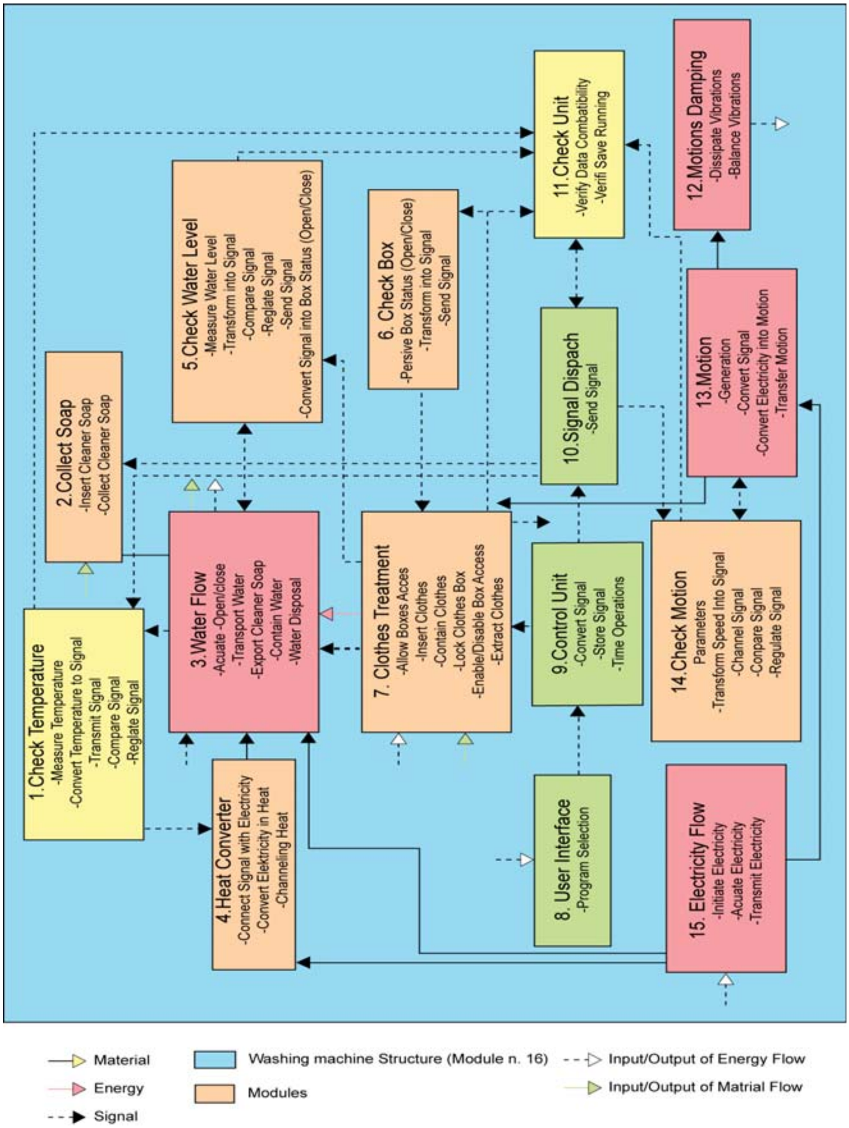

Fig. 6: The modular configuration

In the modular configuration diagram the number of SEM flows is quite reduced because only external flows to the modules must be reported confirming the necessity of modules interaction minimization principle. The "structure" module does not appear in the figure 6 where it has been represented as the background box. Obviously it interacts with the majority of washing machine modules especially where an external input or output is present.

Different product architectures have been proposed to convert modular functions to solution principles. For each of product architecture a modular matrix has been completed with *Implementing* and *Environmental* relationships. Regarding specific product architecture the method starts by analyzing the module solution principle.

Examples of relationships may be as follows. Refer to figure 3 for relationships classification and to figure 7 for a snapshot of the results.

R212 (direct external / standard / overall size): *External structures must respect household appliances standardized dimensions and interfaces*.

R142 (direct internal / rule / overall size): *Structure must geometrically contain all other modules*.

R221 (direct external / performance ergonomic / geometry): *Water container position should be as high as possible to facilitate operation*.

R223 (direct external / performance / dimension): *Soap container dimension should be related to desired amount of soap to store*.

	2.Collect Soap	3. Water Flow	4. Heat Converter	7.Clothes Treament	12. Motions Dumping
2. Collect Soap	-	M24	M24	M27	M212
3. Water Flow	-	-	M34	M37	M312
4. Heat Converter	-	-	-	M47	M412
7. Clothes Treament	-	-	-	-	M712
12. Motions Dumping	-	-	-	-	-
13. MotionsGeneration	-	-	-	-	-

	Relationships that Embody SEM Flows		Additional Relationships	
	Environmental	Implementing	Environmental	Implementing
M 34		l)		
M 37	k)	g)h)i)		
M 713		l)		
M 216	d)	f)	b)	a)
M 316	c)		b)	a)
M 716	e)		b)	a)
M1216		m)	b)	a)

Fig. 7: A part of the washing machine modules matrix**.** A part of the mapped matrix between relationships and modules

In a parametric 3D environment the layout configuration (figure 8) has been defined in order to accomplish geometrical, dimensional and positional relationships collected in the module matrix. Each module has been represented by simplified geometries such as boxes, cylinders, pipes etc, and position relationships have been fix by parameters and constrains between this elements, axis and planes.

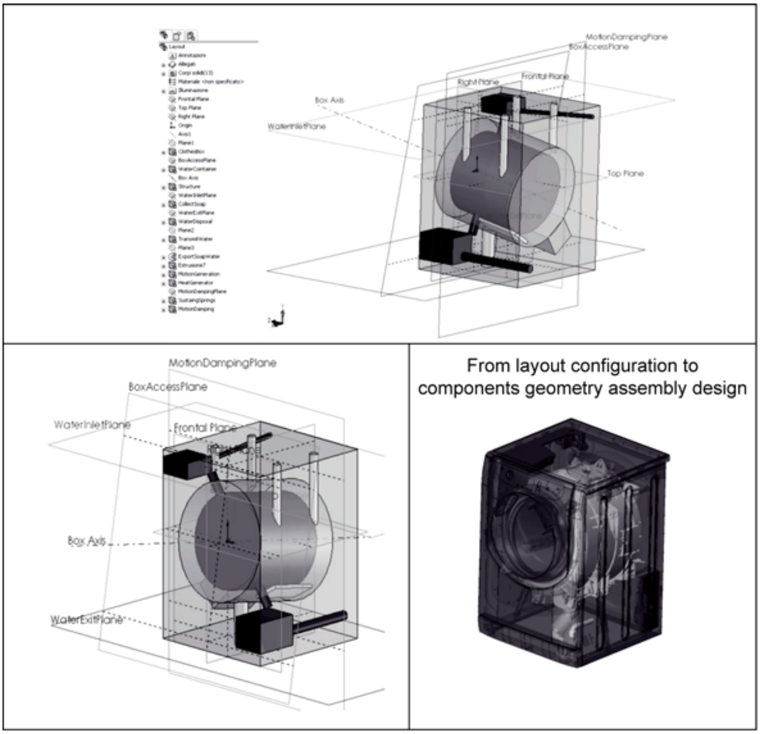

Fig. 8: The layout configuration and the component geometry assembly design

5 Conclusions

The framework presented in this work is a step toward the automation of product configuration. The framework is based on a multi-level structure able to handle multiple views of a modular product, and on objects encapsulating different product knowledge typologies. They make reference to functional information, which are then mapped into modules, and structured in product instances/architectures. This paper has emphasized how function structures facilitate intelligent system decomposition and integration analysis. They support the configuration process providing the information with an appropriate degree of abstraction/detail, on the basis of the specific conceptual design phase. The multi-level product structure described in this paper demonstrates the effective strength of graph-based approaches: concise, visual representation of complex systems. The current design technologies have been used to develop a preliminary prototypal configuration system based on the modular structure, considering also new typologies of relationships (*environmental* and *implementing*). An example (washing machine) is presented in the paper to illustrate how the approach could be used in practice.

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Dependency of the Product Gestalt on Requirements in Industrial Design Engineering

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Abstract
This contribution demonstrates the importance of good industrial design engineering with regard to product development. The strong influence on the product gestalt in different industries (e.g. capital goods, consumer goods) and the added value of industrially designed products are shown in examples [6].

Keywords
Industrial Design Engineering, Product Gestalt, Product Structure, Requirements

1 Introduction

Nowadays many products hardly differ in their technical characteristics. Therefore, many enterprises try to acquire new customers by differentiating their products from competitive products by means of an added value. Among other things, this added value depends on ergonomically compatible and aesthetically designed products which allow an intuitive operation and a customer-friendly use. For this reason, the industrial design engineering, i.e. the specific user-friendly design of products, became more and more important. In future, with regard to technical products developed in high-wage countries, this upward trend will allow enterprises to differ from imitators.

Although technical requirements (e.g. physical operational principles, fabrication, etc.) are already very well integrated into the product development process, often the industrial design engineering is not sufficiently taken into consideration. Mainly the requirements of perception and identification as well as of operation and use ([4, 5]) entail the incisive characteristics a product should have in terms of the aforementioned added value [6, 7].

2 The specialist: Who are Industrial Design Engineers?

Industrial Design Engineers are specially focused on enabling one or more customers to use the performance of a product. Their work during the product development is based on scientific knowledge from ergonomics, work science and psychology.

According to [6] the activities of industrial design engineers can be classified into four main sections:

- Operation:
  Manipulation of a product. Indicators and control elements are counting to these category(e.g. regulate the feed motion, operation of the turn signal) [5, 6]
- Use:
  Use of the technical function of a product. Handholds, ladder, doors etc. are counting to these category (e.g. Seat of a motorcycle, door handle at a car)
- Perception:
  Visual, acoustic, haptic etc. positioning of indicators and control elements (e.g. Speed indicator in the direct field of vision)
- Identification:
  Identification optimized product or interface shape (e.g. a car should look like a car, a turning button not like a push button)

The operation comprises all procedures, which concern the setting-up, adjusting or manipulating of a product. Parameters of the technical function are changed (indicator) and the user gets the feed back of the changed parameters (control elements). The design of a control panel, e.g. for a machine tool, is classical tasks. A panel Cutter e.g. is operated when the saw blade position is adjusted (Fig. 1 left) and used when it separates panels (Fig. 1 right).

Using takes place, if a user uses the technical function of a product for itself or for others (e.g. sitting on a chair, pushing a lawn-mower).

Operation and use could occur at the same time. This happens whenever the user changes the technical parameters during the use of the technical function (e.g. driving with a car with simultaneous manipulation of the steering wheel for changing direction).

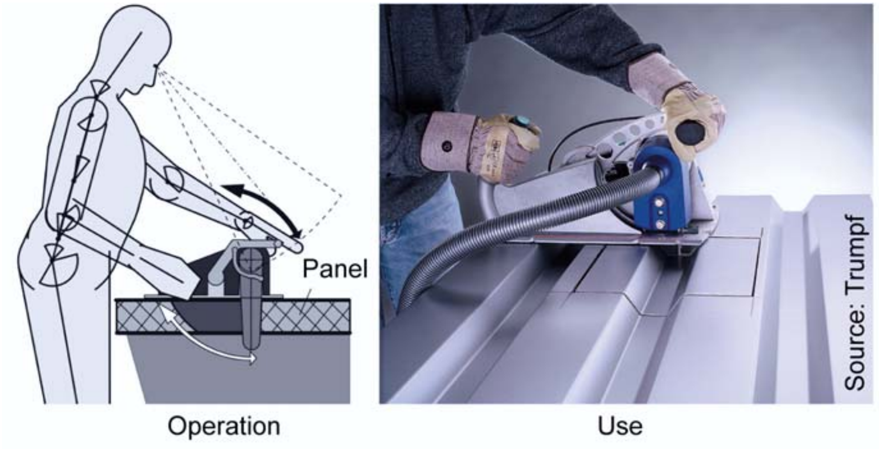

Fig. 1: Operation and use shown with a Panel Cutter

The last two sections, perception and identification, are also linked very closely, that only the view of both sections can lead to an optimal result in a product development. The perception includes the sense of face (visual), sense of hearing (auditory), sense of touch (haptic), sense of balance (vestibular), sense of smell (olfactory) and sense of taste (gustatory).

The identification of a sensory impression is a cognitive process, which compares the perception with known elements. So the perception os interpreted depending on the user's knowledge. The shape can be seen as the letter „H ", binoculars, one H-section or even two skyscrapers, which are connected with a bridge.

The identification of objects always depends on the context, in which they occur, and so, on the kind of perception. For industrial design engineers humans are located in the center for each product development. On the main focus is the user, in addition, service persons or assembly workers can be considered as well.

3 The Object: General Product Structure

Products can generic classified into the following categories [3]:

- services (e.g. financial services)
- software (e.g. dictionary, computer program)
- hardware (e.g. Machine tool, bicycle)
- process materials (e.g. lubricant)

The products, which this contribution is focused on, are located in the category “hardware”. For these products usually one or more parts are manufactured and mounted together to an assembly [9].

Products could be observed for different aspects. Depending on the perspective manufacturing, assembling, using or aesthetics can play a role. For the general view on a product the following product structures can be used:

- assembly-oriented,
- function-oriented and
- characteristic-oriented.

3.1 Assembly-oriented Product Structure

The assembly-oriented product structure is the well-known view on a product. The division a product results from the parts and assemblies. The last ones can contain further subordinated assemblies and parts. A hierarchical structure emerges [1], (Fig. 2).

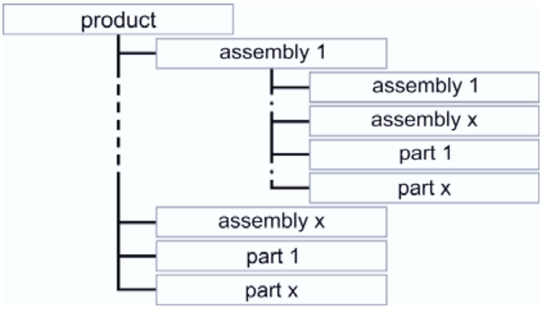

Fig. 2: General assembly-oriented product structure

3.2 Function-oriented Product Structure

A product has an overall function, which can be divided in sub-functions. These sub-functions are classified, depending upon relevance, in main and auxiliary functions [9].

Such functions are reflected, depending upon kind of function, in three different gestalts of a product [6], Fig. 3:

- Function gestalt:
  all elements, which are necessary for the technical function (e.g. Transport from A to B: Wheels, engine, transmission, …)

- Interface gestalt:
  all elements, which make the technical function usable for the user (e.g. Seat, steering wheel, speed indicator); the man-machine interface
- Structure gestalt:
  all elements, which are necessary for the adjustment and protection of the function and interface gestalt (e.g. chassis, housing)

Fig. 3: Function-oriented product structure of a motorbike (gestalts grey shaded)

3.3 Characteristic-oriented Product Structure

The characteristic-oriented product structure, contrary to the two described above, contains the product characteristics which can be created. This structure builds a bridge to the concrete realisation of requirements to a product.

According to DIN 4000 [2] a characteristic is a certain property, which describes and differentiates objects within a group. This definition is used here to differentiate the group „products“ in itself. The characteristics, which are will be used in the following, are selected so that they define a product completely. Other product characteristics (e.g. weight) can be reached by combinations of these fundamental characteristics (e.g. gestalt assembly, shape and material).

The product can be divided, according to the characteristic-oriented product structure, (Fig. 4) [6] in:

- Assembly gestalt: Elements (kind, amount, size) and arrangement (kind, number)
- Shape: Elements (kind, amount, size) and arrangement (kind, number)
- Surface: Elements (kind, amount, size) and arrangement (kind, number)
- Colour: Elements (kind, amount, size) and arrangement (kind, number)

- Graphics: Elements (kind, amount, size) and arrangement (kind, number)
- Material: Elements (kind, number) and arrangement

Assembly gestalt, shape, surface, colour and graphics are according to [6] the partial gestalts of a product. The material has a special role with this product structure. It completes the product gestalt (assembly gestalt, shape, surface, colour and graphics), i.e. the appearance of a product, to a complete product.

The phase, when the materials are chosen, during the product development process cannot generally be fixed. In some cases e.g. a production-correct material is determined, for which the product shape is developed, or material is selected according to the developed product shape. Because the position of choosing the material is thus flexible, the material is neglected in the following views. In the requirements the material is listed again as a characteristic which has to be defined.

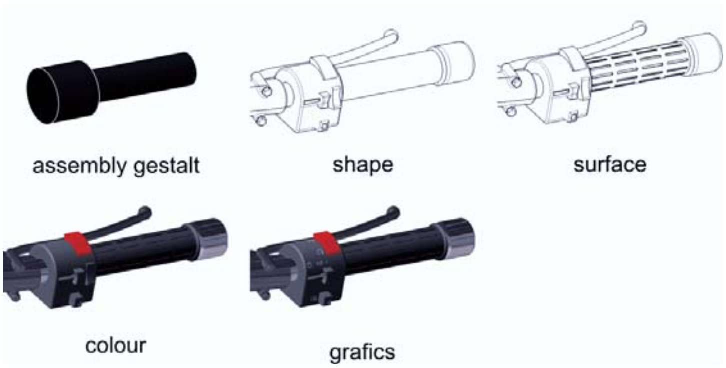

Fig. 4: Assembly gestalt, shape, surface, colour and graphics on a motorbike hand grip

The characteristic-oriented product structure contains additionally to the structure already a given order, in which the characteristics should be defined (Fig. 5).

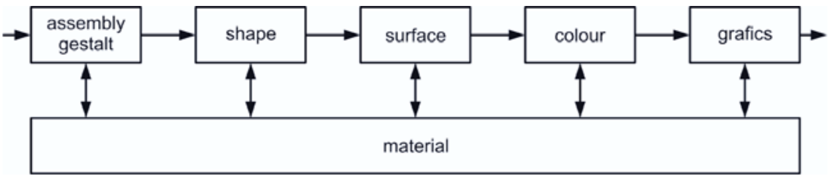

Fig. 5: Process of the characteristic-oriented product structure

The most abstract form of the description of a product is its assembly gestalt, i.e. the arrangement of the building groups and construction units to each other. After that shapes (geometry) on this structure can be applied, followed from surfaces, colour and diagram. To turn this specifcation sequence of the characteristics around (graphics before shape) makes no sense, because this would require additional loops during the product development process.

3.4 Combined, General Product Structure

Every one of the presented product structures illustrates the product complete. They could be used individually for each question aspect of the development. The combination of the three structures, united to a general product structure (Fig. 6), offers the most holistic view on a product.

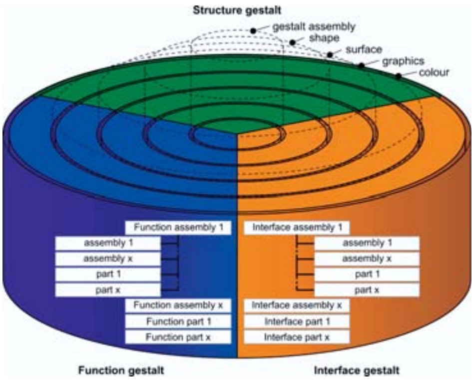

Fig. 6: General product structure

Cylinder top surface:

- Function-oriented product structure:
  rough classification into function gestalt, interface gestalt and structure gestalt
- *Characteristic-oriented product structure:*
  forms the sub category of function gestalt, interface gestalt and structure gestalt, which consists in each case of the partial shapes gestalt assembly, shape, surface, colour and graphics.

Cylinder nappe:

- Characteristic-oriented product structure:
  Function gestalt, interface gestalt and structure gestalt can be seen as assemblies, which consist again of parts and assemblies. The assemblies and parts again have assembly gestalt, shape, surface, colour and graphics.

By the creation of this general product structure the product can subdivided into elements (e.g. assembly gestalt of function assembly or structure gestalt colour of a structure gestalt part). Each of these elements have to be defined during the product development process, and have to be joined to a whole product. That means, if each element of this general product structure and its joining element are defined, the product is completely defined and the product development process is finished.

4 Human-product Requirements

Industrial design engineers are developing under a user-centred view. Because of this they are interested in the human-product-requirements. The general people product requirements are specified in the following:

- Design for human (user, assembly worker,…)
- Design for Operation
- Design for Use
- Design for Perception
- Design for Identification

A complete human-product-requirements list is shown in Fig. 7.

5 The Method: Matrix of Influence

Now that the product and its elements, which can be defined, as well as the general human-product-requirements are known the dependence between both of them can be identified.

For matrix of influence shown in the Fig. 7 is suitable. It illustrates in general two different influences:

- human-product-requirements influencing the product (area A)
- human-product-requirements influencing among themselves (area B)

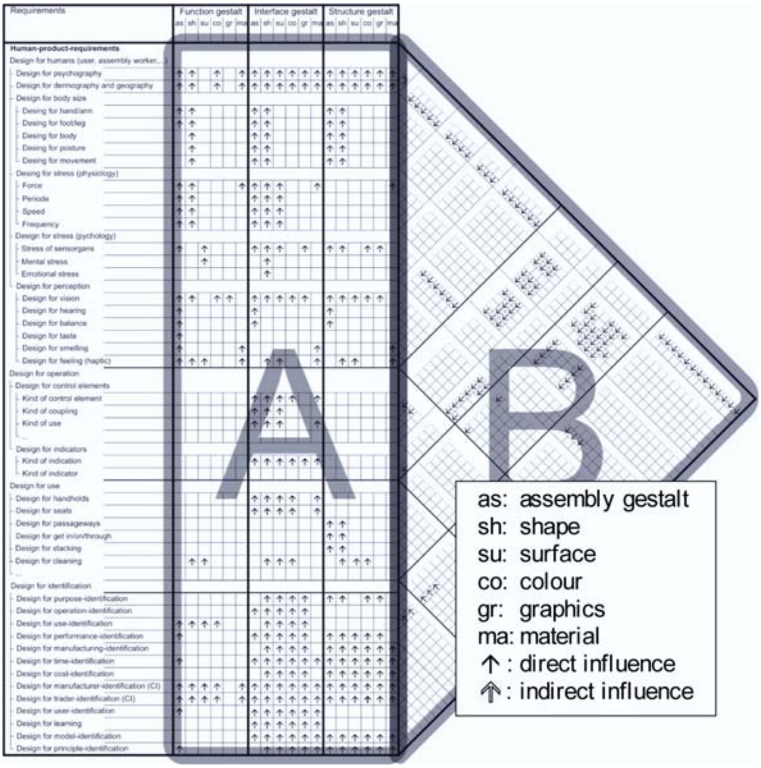

Fig. 7: Matrix of influence with human-product-requirements and product structure

Influences are marked by arrows, whereby the direction of the arrow is similar to the direction of the influence (e.g. assembly gestalt of function gestalt → kind of control element: assembly gestalt of function gestalt is influenced by the kind of control element)

The influence on the product by the human-product-requirements is exemplary described in Fig. 8.

Results of the described influences could be consequences for the product development process. As previously mentioned the characteristic-oriented product structure includes a process, which steps build up one on the other. E.g. specification of the assembly gestalt of the function gestalt is directly followed by specification the shape, surface, etc. of the function gestalt. The change of these early specifications later on in the process de-mands to return each step until then, because there could be a effect on these following steps.

The human-product-requirements are in this context very important, because they can determine significant the assembly gestalt of a product. The integration of these requirements in late phases can happen only partial or at the expense of other requirements.

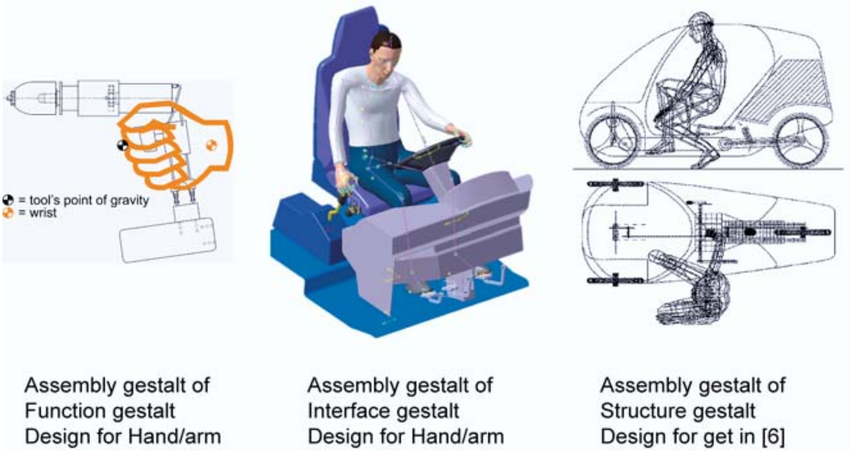

Fig. 8: Exemplary influences of human-product-requirements on the product

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Synergy of Technical Specifications, Functional Specifications and Scenarios in Requirements Specifications

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Abstract
In the (mechanical) design process, the requirements specification is a formal registration of the conditions that are imposed on a new or altered product design, both preceding as well as during the corresponding product development cycle. For a long time, the use of technical specifications has prevailed in the establishment of such requirements specifications. However, gradually, there is an appreciation for the fact that sheer technical specifications may inadvertently fix constraints and possibilities too early in the process. Moreover, it is recognized that technical specifications are unsuitable to adequately address the role of unquantifiable aspects that play important roles in the development cycle. Using functional specifications and scenarios respectively may aid in addressing these problems. Considering the importance of having an effective requirements specification, the coherence, synergy and specifics of technical specifications, functional specifications and scenarios as part of the requirements specification are addressed. This publication focuses on the different roles, limitations and added values of the constituents of the requirements specification.

Keywords
Requirements specifications; Technical & functional specifications; Scenario based design

1 Introduction

In product development cycles, stakeholders constantly deliberate about alternative solutions to design problems. This observation stresses the importance of decision making processes for the overall effectiveness and efficiency. Requirement specifications serve as a reference for judging the available decision alternatives. As such they have a large impact on the course of development cycles.

Requirement specifications exist in multiple appearances, differing in e.g. level of detail, certainties and ambiguities. In this paper, three types are distinguished: technical specifications, functional specifications and scenario based specifications. The amalgamation of the different requirement specifications constitutes a dynamic frame of reference. The frame evolves with the product definition, providing a benchmark for assessing the current development cycle and prefacing subsequent development processes.

2 The Product Development Process

Product development comprises of the processes that transform the needs of the customer or the marketplace into a product that satisfies these needs. In general, it is a process conducted by designers and engineers, involving many other stakeholders. Although the composition of such product development teams may seem rather intangible, usually there are clear (though possibly implicit) motives to bring together the expertise and domain knowledge of the people involved. Within the context of the organisation, the customer (type) and the type of product to be developed, the development team can address the specified need by means of an agreed upon design method.

Traditionally, such design methods originate from the process oriented description of the activities that together prospectively give an adequate coverage of the expected development trajectory. Whether these methods stem from empirical research on the activities of designers or from theoretical discourses on the nature of the development process, habitually they endeavour to capture the development process in a set of addressable, coherent and mutually dependent process blocks (e.g. Pahl and Beitz 1995; Ullman 2003; Andreasen 1987). Most design methods appreciate the need of the product developer to reconsider earlier decisions or to revise part of the development cycle to assess product variants. In doing this, reaching decisions becomes a distinct constituent of the development cycle.

2.1 Evolution of Product Definition

From a decision oriented point of view, the development cycle can be seen as a concatenation of decisions, which – because of their impact and sequence – is determinative for the course of processes and the result (see e.g. Jin and Lu 2004). In elaborating this reasoning, design essentially is an exercise in problem solving. Without canonising this statement, it does give a broader view on the development process: the processes as described in design methods are not the only driving forces in the development process. In order to exploit this adequately, the underlying information content of the development cycle has to be determined explicitly in a structured and accessible manner. Consequently, the combination of processes, information and decisions structure can become the flexible instigator of the development process (Lutters et al. 2004).

2.2 Requirement Specification

As a consequence of this changed perception, the requirement specification need no longer be the result of the initiation/revision in some of the design stages. Instead, it can become one of the contributing entities to facilitate the entire development cycle. Here, the notion requirement specification is defined as the registration of the constraints, demands and wishes that are established to state the design problem and its envisaged solution.

2.3 Evolvement of Product Definitions

If product development can be instigated by the requirement specification, the information content and the available process descriptions, much more flexibility can be incorporated. The advantage is that there is no longer a need to pre-specify the entire development cycle in terms of processes. Any decision – based on the current information content and the current traits of the requirement specification – can , and will, cause changes, improvements and additions in the foreseen process steps, but also in the information content and requirement specification. Especially the latter influences are important, as they imply that both the information content and the requirement specifications are 'living' constituents of the development cycle. They not only give the most up-to-date representation of the product definition, they also evolve during the entire development cycle. It is this evolvement, that enables a much more flexible, tailored and effective way of relating the advancements in the product development cycle to adequately resolving the initial needs of the customer or the marketplace.

3 References for the Design Process

When decisions are considered instigators of the development process, the nature of the available context for taking a decision becomes increasingly important. The requirement specification can serve as a frame of reference through the entire development cycle and as such is an indispensable part of that context. Throughout the development cycle, the subject of the decisions will change with respect to level of detail, level of aggregation, considered domains, etc. To support a well-substantiated decision, the expression of the requirement specification must ally with the characteristics of the decision at hand. As a structure for the alliance, three types of requirement specification can be discerned: technical specifications, functional specifications and scenario based specifications.

All specification types comply with the stated purpose of the development process, which is a predefined, formalized and static reference of that development process. Therefore, the stated purpose reflects the pre-imposed requirements of (external) stakeholders, like law, marketing and safety. Due to its static nature, this type of reference hardly influences the selection and use of the different requirement types.

3.1 Technical Specifications

Technical specifications are complete and unequivocal expressions of product requirements. They address e.g. the minimum wall thickness of a beer bottle, the power to weight ratio of a motorcycle or the nominal size plus tolerance of a shaft in a sub assembly. In general, technical specifications express quantitative or easily quantifiable demands.

3.2 Functional Specifications

Functional specifications provide a description of desired future product behaviour. In general, they express concrete demands to abstract product models. As an example of functional specifications, consider a beer bottle falling of a table. The bottle is required to stay in tact after the fall.

3.3 Scenario based Specifications

In product specifications based on scenarios, emphasis is being placed on the product's environment and the interaction between product and its environment. Product behaviour is indicated in terms of what the environment, e.g. the user, can do with a product and how it will interact as opposed to technical or functional specifications where traditionally focus is placed on what the product will do and how it does it.

Scenarios are hereby defined as explicit descriptions of hypothetical events concerning a product during a certain phase of its life cycle. This approach is useful when exploring less quantifiable influences on the product life cycle, such as the usage of a product. However, product specification based on scenarios can as well be applied to address for example the maintenance or quality management of a product.

A scenario can say what happens in a particular situation without committing to details of precisely how things happen. Furthermore, a scenario can be deliberately incomplete to help developers cope with uncertainty.

The scope of a scenario and its form alters with the aim and stage of the product development process it is used in. It can range from a story about the problem domain as it exists prior to product introduction to a set of hypotheses about product use to evaluate designs (Rosson and Carroll 2002).

As an example, imagine the beer bottle now placed between people throwing a party. The party may in one scenario be a quiet sit-around-the-table situation and in another case involve lots of dancing students. The beer bottle is required not to break during use. Based on the scenarios, developers can judge the relevance of the hazards incorporated by this use.

Fig. 1: Technical, functional and scenario based requirement specifications

4 Appropriateness of Specification Types

When requirement specifications are viewed as an evolving frame of reference for decisions throughout the entire development cycle, insight in the appropriateness of the distinct specifications for different decision types is required for an efficient application of the requirements. The degree of completeness, unambiguity and certainty of the involved information content and the influence of context information in this respect are important.

4.1 Technical Specifications

Technical specifications provide the information content minimally necessary for an equivocal definition of a product model. Therefore, they principally leave little (or no) room for interpretation. The solution space of a design problem is constrained with unambiguous and quantitative demands. These characteristics make them extremely useful as a reference for deciding between fully defined design options. Consider e.g. the minimum capacity and maximum impulse resistance of a beer bottle to serve as a reference for a material choice and wall thickness definition; the product geometry must also be determined with a high degree of certainty in order for the decision to be meaningful.

The minimalist formulation that is characteristic for technical specifications is experienced either positive or negative, depending on the view on its use. From the perspective of e.g. a quality guard, one straightforward interpretation of product properties is desirable. A development engineer however will miss the context that led to the formulation of the specification afterward changes have to be implemented.

4.2 Functional Specifications

When the information content related to a decision is still relatively uncertain and incomplete, functional specifications can describe the product behaviour. The realization however is still an open question. Humans are uniquely qualified to deal with such non-deterministic decisions. Functional specifications can guide the decision making process.

The description of a desired behaviour pretends to give an objective perspective on the future. However, the description of a certain desire by definition is subjective and the future behaviour of products therefore cannot be objectified. Moreover, functional specifications principally are defined on their own. Their possible mutual dependencies are not reflected. Possible conflicts therefore are not revealed.

4.3 Scenario based Product Specification

The use of scenarios as a frame of reference in the development process originates from discipline of software engineering. The advantages of specification based on scenarios identified for software engineering (Rosson and Carroll 2002) are also applicable to the field of product design.

Scenarios for instance can be very useful in managing the tradeoffs among competing design goals as they allow making decisions but at the same time to keep options. Scenarios allow for exploring ideas and obtaining feedback, whereas they can be revised quickly and easily, helping to avoid premature commitment. Scenarios also allow incorporating the influence of the environment on the functioning of a product and visa versa in the development process by explicitly foreseeing the co-evolvement of the environment with product interactions. Scenarios therefore allow relating the requirements placed on the product to its environment, even if the environment is dynamic (Brouwer and Van der Voort 2006).

However, if certain product features can be quantified, for instance since they are prescribed by external factors, these characteristics are less easily incorporated in a scenario. It should also be considered that the power of scenarios is to represent alternatives, explore boundary conditions and enable comparisons. Therefore always multiple scenarios from different points of view need to be created to obtain an accurate overview. A scenario or even a set of scenarios is by nature incomplete without revealing to what extent.

5 Compound Requirement Specification

The solution space in which product development processes are allowed to take place is determined by the frame of reference. The specifications constituting the frame serve as an argumentation and negotiation basis for taking design decisions. In many cases, the specifications will be clear and unambiguous. However, especially in the early stages of a development trajectory, they can be uncertain, incomplete and even contradicting. In order not to introduce feint certainties in the process, it is important to adequately represent specifications applicable to a certain decision.

5.1 Dynamic Requirement Specification

When the frame of reference is constituted by evolving requirement specifications (see chapter 2), the relations between the specifications must be dynamic as well. The product definition will concurrently evolve on different levels of aggregation, instigated by different viewpoints and with respect to different aspects. For the requirement specification to serve as a reference in the entire solution space, it must therefore be possible to interrelate the information constituting the different specification types.

5.2 Different Views on Frame of Reference

The different types of requirement specifications constitute the same solution space but show considerable differences. The differences stem from the perspectives on that solution space. A focused perspective for example expresses detailed, high-certainty constraints whereas a broad perspective portrays a design decision in its context.

When viewed from different perspectives, the same requirement information can be denoted in different ways. The structure of the frame of reference specifies the relation between the different viewpoints. Following these relations, translations from one specification type to another can be made. There are two pitfalls in doing this. In many cases, only the new denotation is represented, losing information from other perspectives. Such a translation for example is useful when presenting quality requirements to a machine operator: in his work the functional reasons for the requirements are not relevant. The other pitfall is to include both broader and narrower perspectives. No information is lost in this case, but the uncertainties in the presented information increase.

When the translation of requirement information is governed by the evolution of the product, the convergence in the development progress will make the uncertainties gradually decrease (Lutters 2001). At the end of the development process, the frame of reference has become an inherent part of the product definition, giving justification for design decisions. Moreover, it becomes a benchmark for estimating completeness, uncertainties but foremost possible pitfalls and bottlenecks of the overall development cycle and subsequent cycles.

6 Application in Development Cycles

In development cycles, two types of phases can be distinguished: diverging and converging phases. Due to their different natures, the phases require different support methods to establish increased process effectiveness and efficiency.

In diverging phases, adequate support facilitates the generation and evaluation of explicit product information from abstract ideas. A dedicated work environment for performing product development tasks can offer such support by assessing a design in different contexts. These environments are called Synthetic Environments. In Synthetic Environments, the use of a.o. media and Vitual Reality techniques triggers the use of the associative capacities of the stakeholders involved in the performance of the task. They therefore allow development activities based on aggregate influence factors.

For this support to be beneficial to the effectiveness and efficiency of the design process, the Synthetic Environments must use an explicit, but not necessarily decomposed representation of the requirements for reflecting new ideas within the boundaries of the stated purpose. In a Synthetic Environment, technical and functional requirements are not enough to attain oversight in the early phases. They also do not give much insight in the interrelations and reasons for existence of certain requirements. Typically, scenario based requirement specifications therefore have the added value to let stakeholders, regardless of their disciplinary background, experience the aggregated quality of their ideas.

In later stages of the development cycle, the divergent product information must be combined in one coherent product model. This process generally requires much iteration; the many, often conflicting, product properties must be brought in harmony, but a change in one aspect induces consequences for the validity of the model with respect to another aspect. In the so-called What-If design method, these relations are modelled explicitly (Lutters et al. 2004). This allows an automatically generated overview of the possible consequences of a design change. A condition for this type of support to be implemented is that the functional and technical specifications within which changes are allowed are modelled adequately. Moreover, in order to warrant the significance of the product model for the stated purpose of the development process, the modelling must be in harmony with the more general picture of the requirements as agreed upon in previous stages of the design process. This observation stresses the importance of a coherent frame of reference for the entire design process that can be viewed from different perspectives, depending on the need for a specific representation.

7 Concluding Remarks

From a decision oriented perspective on design processes governance, requirement specifications should be an evolving (“living”) constituent of the product definition. This allows their content to be directly influenced by design decisions while their expression at the same time serves as an up-to-date frame of reference for taking decisions throughout the entire development cycle. The three distinguished expression types, i.e. technical, functional and scenario based requirement specifications, stem from different perspectives on the solution space. Essentially, they are different denotations of the same requirement information. Based on the (dynamic) structure of the frame of reference, translations can be made from one type to another. Evolutionary governance of the translations will make the uncertainties enclosed in the requirements gradually disappear; in the end making the frame of reference an adequate benchmark for process assessments. More research on the use of the frame is however necessary to uncover the possibilities for exploiting this advantage. Upcoming research on this topic will focus on the advantages of the frame of reference for the application areas of Synthetic Environments and What-If design.

8 Acknowledgement

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Modeling of Heterogeneous Systems in Early Design Phases

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Abstract
In the past it was often adequate to assemble an overall system from separately developed and optimized parts. However, recent developments in engineering show the need to integrate mechanical, optical, electrical, electronical and software components. This new quality of interdisciplinary collaboration requires new computer-aided, phase- and domain-spanning tools for modeling, analysis, simulation and optimization of complex design objects particularly in the early phases of product development. The article covers the first intermediate results of the ongoing research concerning a phase-overlapping design system for heterogeneous systems that supports the transition from the solution principle to embodiment design.

Keywords
Heterogeneous Systems, Early Phases of Product Development, Constraint-based Modeling

1 Introduction

For computer-aided modeling and calculation of heterogeneous systems different approaches are known. Some of them already allow an holistic development process for (usually mechatronic) components and products.

The following categories exist:

- general simulation systems,
- specialized simulation systems,

- parallel application of multiple simulation systems,
- guidance and assistance systems and
- integrated solutions.

For the design and particularly the simulation in early phases **general simulation systems** can be applied. These systems are flexible since modeling is done by entering source/script code, equations or schematic diagrams that describe and simulate heterogeneous systems on a functional level. However, this approach leads to a number of disadvantages. It is often difficult to derive equations that represent functional properties and to incorporate structural properties (e.g. function-relevant positional relations of mechanical and optical components). Also, there is usually no support for the transition from the functional description to the embodiment.

Specialized simulation systems are usually not suitable for holistic modeling and simulation of heterogeneous systems. For instance, the modeling system for electronic circuits SPICE allows limited handling of non-electronic components that have to be transformed into equivalent electronic or electric circuits. It is not possible to model components for feedback control systems [4]. Serious limitations concerning a uniform equivalent description of heterogeneous systems also exist in dynamic simulation systems (e.g. ADAMS, ALASKA, SIMPACK, ITI-Sim), in software for control theory (e.g. FSIMUL, SIMULINK) or in optics simulation systems (e.g. OSLO, ZEMAX, DIFFRACT). None of these systems closes the gap between the solution principle and the embodiment with focus on the transition between the two representations.

The parallel application of multiple simulation systems considers the necessary multidisciplinarity of the design of heterogeneous systems as the user applies a number of different, domain specific softwares that support modeling, analysis/simulation and evaluation/optimization. This approach demands a high degree of design experience and the mastery of many software products. Also, redundancies and loss of information are inevitable in such a process. To avoid the resulting additional expenses, it is reasonable to join the different softwares that cover only narrow fields f representation, calculation, simulation and optimization.

One possible approach for this are **guidance and assistance systems** [1]. These provide a methodical guide with specifications for merging the data of a design object in a uniform repository of data. The core of such systems are usually CAD systems that are linked with other softwares to support the design of certain products or product groups.

Also, modern CAD systems are able to provide **integrated solutions** for several problems concerning the design of heterogeneous products.

Typically, this is done by adding customized add-on modules for certain scopes of problems offered by various vendors. Examples are add-ons for multi-body simulation (e.g. Autodesk Inventor and ALASKA), for the finite element method (e.g. SolidWorks and COSMOS) or for design of drives and controllers. However, there is no CAD system that covers the whole spectrum of requirements for the design of heterogeneous systems.

In conclusion, the mentioned approaches show deficiencies concerning the domain-overlapping description of heterogeneous systems and the phase-overlapping modeling from the functional description to the embodiment design.

2 Constraint based Modeling

Models of heterogeneous systems can be seen as a set of components and a set of relationships between these components. In the following text these relationships are referred to as constraints.

Usually Constraints are defined between the parameters which describe the properties of the components (shape, position, material, physical and electrical properties, etc.). If the parameters have values such that all constraints are fulfilled, the model is called to be consistent.

After changes of some parameters (e.g. during an optimization) or even often in the initial state the constraints are not fulfilled. Then calculations have to be performed to find new values of dependent parameters which make the model consistent (Fig. 1). In addition to constraints which reference values of parameters (e.g. those parameters describing more complex elements like cylinders or rays) some types of constraints control the existence of such elements or components. This includes the existence of the single parameters as well as according constraints referencing the parameter values. In general constraints can be defined by modelers in very different ways [6], e.g.:

- equations and inequalities (very general formulations),
- clauses in predicate logic (e.g. to handle existence),
- fuzzy relations (to represent fuzzy information) and
- domain specific relations (often those relations cover sets of values, e.g. position parameters in assembly constraints).

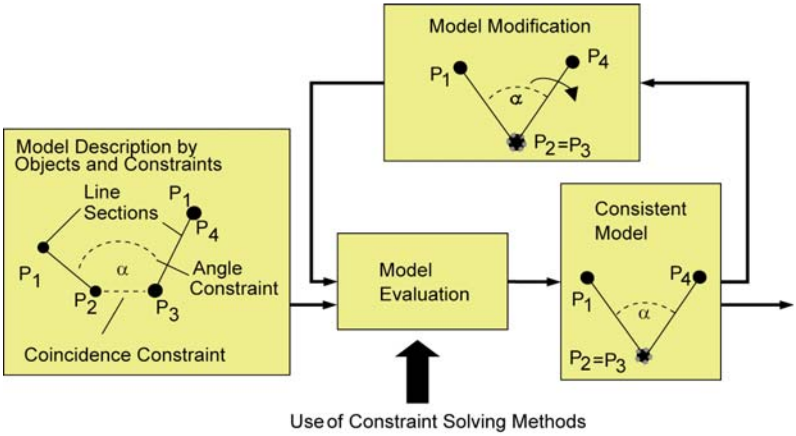


Fig. 1: Calculation cycle in constraint based modeling. After an initial definition or later modifications the constraint solver has to calculate new values to ensure the consistency of the model. If not all constraints can be satisfied different strategies can be used, e.g. restoring the last consistent state, minimization of the errors (optimization) or ignoring certain constraints (that means a mechanism could break)

Domain specific relations like assembly constraints may be formulated as equations and inequalities too. During such a transformation domain specific information is lost, thus it can not be used in the calculation process. If the domain specific information about the semantics of relations is kept then appropriate calculation modules can be chosen and the handling of such relations becomes much more efficient (example: iterative solution of mostly non-linear equations using Newton-Raphson method vs. geometric constructions using a ruler and compass approach). Furthermore special cases (e.g. degenerated cases, multiple solutions) can be handled in a way which is expected by the user. For interactive work both advantages of using domain specific information are important. The engineer should realize the consequences of his design decisions (e.g. chosen parameter values and according product properties) as fast as possible and he should never be irritated by the presentation of solutions which are formally correct but totally unexpected. A very simple example is shown in Fig. 2.

This shows that the heterogeneous formulation of heterogeneous systems is reasonable according to calculation efficiency as well as solution plausibility.

The choice how relationships are to be expressed should be made by the engineer who builds up a certain model. Nevertheless internally in the constraint solving application the model representation may be transformed with respect to available calculation modules. Quite simple is for instance the transformation of geometric constraints into equations. The inverted direction (extraction of geometric constraints from equation systems) is more complicated in general. As an example a distance constraint between two points may be used. For its detection the variables storing the point coordinates must be identified (the number of coordinates depends on the dimension) and a further parameter must be identified as the distance. The quadratic equation which references these parameters is a strong hint that the engineer had the intension to model a distance relation but in general that is not sure.

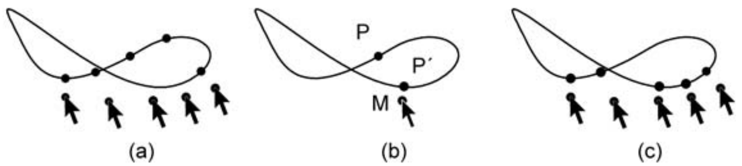


Fig. 2: A point may be moved on a certain path. The path may be defined implicitly by a mechanism. The movement in (a) is an example for a behavior as expected by the user. The calculations ensure that the point stays near to the cursor and that motion on the given path is continuous. (b) shows the point at position P and an alternative position P' which is even nearer to the cursor but the user would not expect this solution because the according movement (c) is non continuous and would irritate him

3 Integration of Calculation Modules

A main problem concerning the calculation to achieve model consistency is the choice and coordination of the calculation modules. This is done by the module manager (Fig. 3). The implementation of this coordinator can be based on one of the following options:

- Transformation of all constraints into equations and inequations (differential equations if necessary) and algebraic (only for small systems of equations) or numerical (initial approximation problem) solution.
- All dependencies are compatible to a single calculation module, i.e. such a module can handle them directly or a transformed version of them. In this case that module alone can generate a consistent model state.
- The model is divided into parts that can be handled by a set of specialized calculation modules.

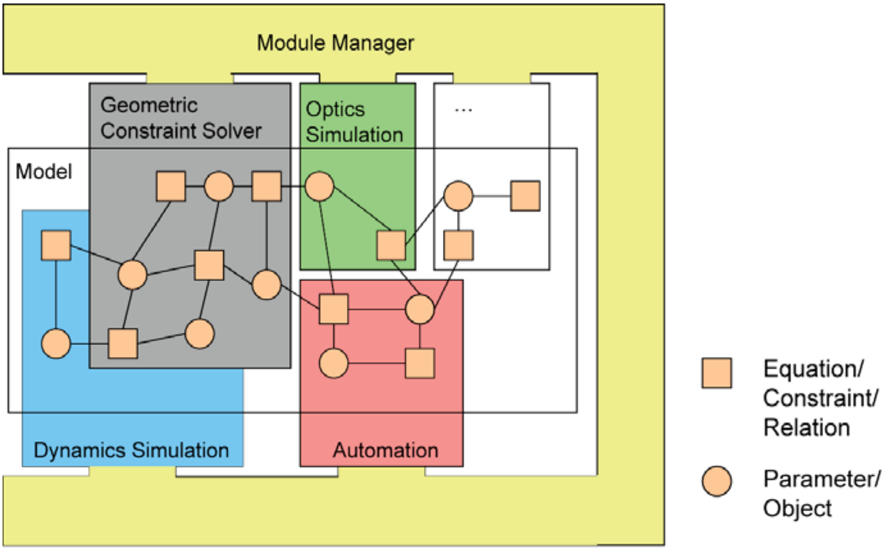


Fig. 3: Specialized calculation modules/solvers handle parts of the model. In some cases a model part can be calculated by more than one module. Then, the module manager decides which module handles this part depending on the task

The latter approach is not only the most general and efficient one, it is also more difficult to implement. Amongst others, the following problems need to be solved:

Segmentation of the Model Parts to be Solved

One aspect is the intention to solve constraints at a high level of abstraction to benefit from the advantages of domain-specific solution methods. On the other hand, in order to limit the complexity of the coordination of the solver modules a few large model segments are easier to handle than many small ones. Therefore it makes sense to support some general solution tools in the specialized calculation modules (e.g. support of simple equations).

Other aspects are the complexity and solvability of the model segments [2, 3]. Particularly important is the avoidance of over-determination.

Coordination of the Calculation Modules

For the calculation methods in each module exist input and output parameters. Input parameters can be constants, output values of other modules or user inputs. The module manager needs to coordinate the modules in a way that ensures a global solution progress, i.e. that calculated parameters of one model segment serve as input values of another segment (sequential approach). Since this is not always possible, an alternating or iterative application of solvers can be necessary. Fig. 4 shows an example for the alternate application of calculation modules. The symbolic representation of the model (slider crank, upper left corner) is a very abstract, domain-specific description (assembly of mechanical elements).

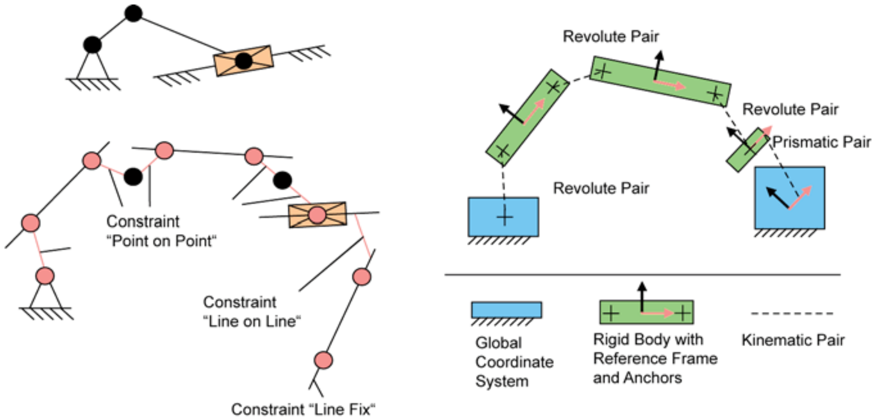


Fig. 4 Transformation of the abstract model description (upper left) of a slider crank into specific representation for a geometric constraint solver (left) and for multi-body simulation (right)

For calculations the symbolic representation needs to be transformed into a solver-specific description. A conversion for a geometric constraint solver is composed of basic geometric elements and constraints (left side). On the other hand, a conversion for a multi-body simulation is described by rigid bodies and kinematic pairs (right side). Depending on the task the used representation (and with it the calculation module) is selected. While the geometric constraint description is favorable for an interactive modeling process, the multi-body representation allows calculations concerning the dynamics of the model.

The described constraint-based modeling approach allows a phase-overlapping description of heterogeneous systems since the generic model representation is independent from visualization and calculation [5].

4 Application Example

As an example for the modeling of a heterogeneous system a micrometer is used. The micrometer is based on a revolvable/pivoted parallel glass plate. This kind of micrometer can be used as an adapter for measuring telescopes. The idea is the generation of a parallel offset from the principal axis by tilting the glass plate (Fig. 5).

With this parallel offset, deviations of objects can be measured in the range of micrometers e.g. by using a knurl with a linear scale.

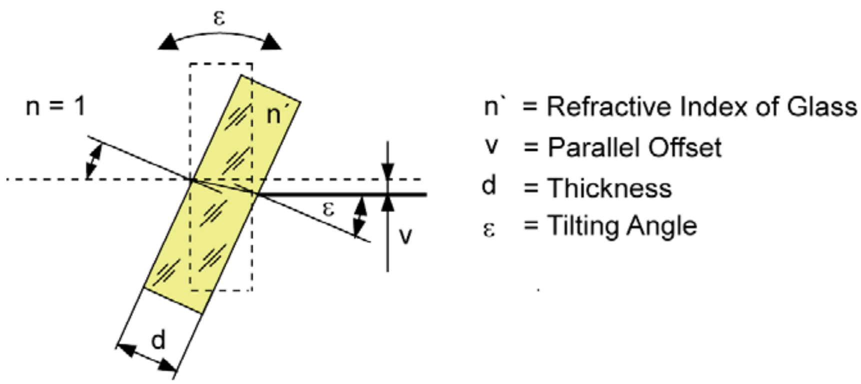


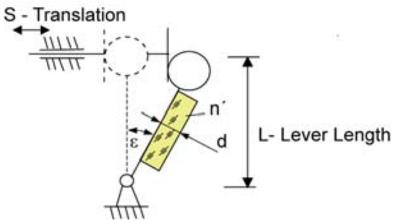
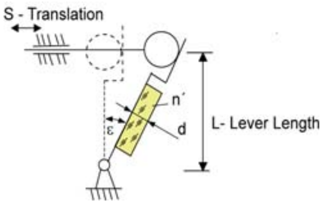
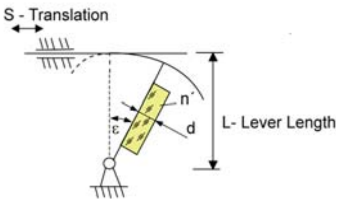
Fig. 5: Parallel offset of the main beam by a coplanar glass plate

Starting point of the micrometer design is the identification of the functional interrelations between the tilting angle ε of the glass plate and the parallel offset v of the main beam. For this identification the application of the law of refraction is necessary. After some transformations the following equation results:

$$v = d \sin\varepsilon \left(1 - \frac{\cos\varepsilon}{\sqrt{n'^2 - \sin^2\varepsilon}}\right) \tag{1}$$

The next step is to find suitable function elements for an adjustment mechanism. For this, a simplification of equation (1) is convenient in order to decrease the design effort by using a knurl with a linear scale. Possible simplifications are the approximations shown in Table 1. These approximations can be found by assuming the tilting angle ε to be small.

Tab. 1: Approximations of the transfer function (1) to achieve linear behavior between input parameter s and tilting angle ε

Approximation	**Solution principle**
$v \approx v_{approx\_\sin} = d \sin\varepsilon \left(\frac{n'-1}{n'}\right) = d\,\frac{s}{l}\left(\frac{n'-1}{n'}\right)$	 sine mechanism
$v \approx v_{approx\_\tan} = d \tan\varepsilon \left(\frac{n'-1}{n'}\right) = d\,\frac{s}{l}\left(\frac{n'-1}{n'}\right)$	 tangent mechanism
$v \approx v_{approx\_\varepsilon} = d\,\varepsilon \left(\frac{n'-1}{n'}\right) = d\,\frac{s}{l}\left(\frac{n'-1}{n'}\right)$	 ε-mechanism

For the approximations in the first column of Table 1 simple adjustment mechanisms as solution principles can be found (second column in Table 1). These principles can be modeled in the parametric design system MASP (Modeling and Analysis of Solution Principles). Thus the determination and verification of function relevant properties are possible.

To evaluate the suitability of the different approximations (Table 1) a comparison with the original function (Eq. 1) is necessary. The calculation of the difference Δv between the parallel offset v_{approx} of the approximations and the parallel offset v of the original function (Eq. 1) can be done using motion simulations (automatic or interactive) of the full-parametric model in the design system MASP (Fig. 6).

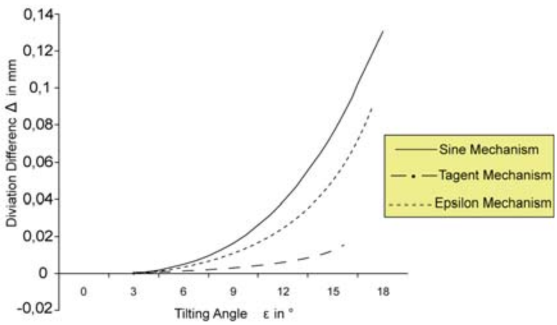


Fig. 6: Difference Δv between v_{approx} of the approximations from Table 1 and v of the original transfer function (Eq. 1) for different tilting angles ε (assumption: refraction index n=1,519; thickness of the glass plate 22,44mm)

As the next step in the design process the adjustment mechanism with the smallest difference Δv to the original function is choosen to maximize the tolerance for errors caused by manufacturing and usage. The selected mechanism must be adapted to other conditions like installation position or sensitiveness of the adjustment mechanism including the knurl (Fig. 7). For this, a number of parameters must be specified with their interdependencies.

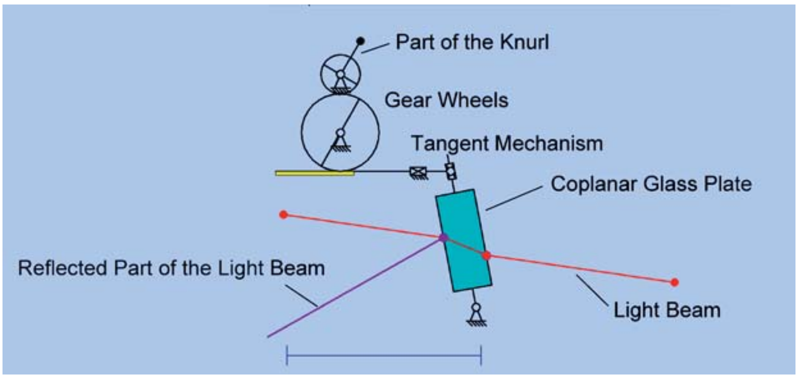


Fig. 7: Solution principle of a micrometer modeled in the design system

Even this simple model allows many modifications by parameter variation (e.g. change of diameter of the gear wheels, thickness or the refraction index of the glass plate, parallel offset of the principal beam). The interactive graphical modeling of the solution principle is based on predefined symbols. The interdependencies between all parameters are handled automatically.

Some examples of modification results are shown in Figure 8.

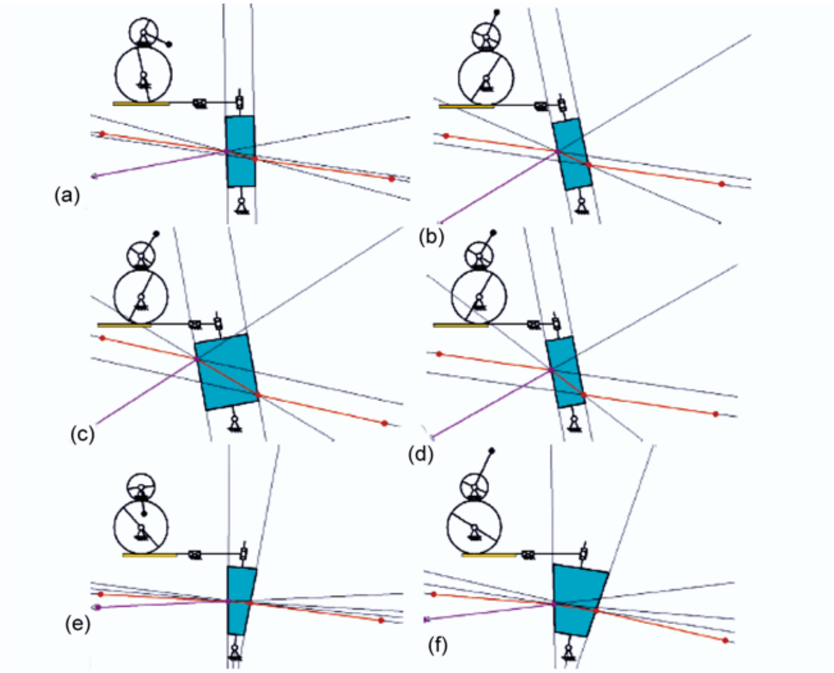


Fig. 8: Modifications of the solution principle of a micrometer modeled in the design system MASP (the shown geometric sub-elements like directed lines illustrate the underlying constraint model). (a) and (b) Calculation of different positions of the micrometer by interactive rotation of the knurl. (c) The variation of the parallel offset with immovable adjustment mechanism and constant refraction index causes a change of the glass thickness. (d) The variation of the parallel offset with immovable adjustment mechanism and constant glass thickness causes a change of the refraction index. (e) The coplanar glass plate changed into an optical wedge. (f) The variation of the parallel offset with immovable adjustment mechanisms and constant refraction index causes a change of the wedge thickness

In this way a solution principle can be adapted to the required function and can be used to generate the first embodiment design. To achieve an easy usability a catalog-oriented design is used in MASP. It supports the user in modeling the intended product attributes (e.g. layout/form, material, technological properties) of the first embodiment design using predefined solution elements in combination with invariant information in the solution principle like certain distances and angles or position of translation and rotation axes. Necessary bi-directional references between solution principle and embodiment design are added automatically during the generation. This allows iterations during the design process without losing the consistency between the model parts that describe the solution principle and the embodiment.

5 Summary

The paper describes a concept as well as the first results of a project that aims to increase the effectivity of the embodiment design process for heterogeneous products. The concept integrates phase-overlapping as well as domain-overlapping design approaches into a computer-aided modeling system aimed at the early phases of product design. The basis for the presented work are solution principles that can be analyzed, simulated and optimized regarding different function-related aspects. The constraint-based modeling approach allows to include embodiment properties of heterogeneous models and to handle them in a holistic way. The optimized solution principles are the basis for the determination of an appropriate first embodiment of the function-relevant mechanical, optical and drive components.

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Requirement-oriented Configuration of Parallel Robotic Systems

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Abstract
Facing the increasing cost pressure, the decreasing product development time and demanded flexibility in today's markets various strategies are conceivable. Within the area of high dynamic parallel robots the use of flexible modular systems for configuration and reconfiguration is one solution approach. In combination with an improved handling of requirements (i.e. a suitable structuring of requirements for the different phases of design process and hierarchy of product elements) and the modeling of inter-model relations (e.g. between requirement, structure and cost models) customer-oriented products can be build up fast.

Keywords
Design Methodology, Product Development Process, Requirement Management

1 Introduction

Today's products become more and more complex and use various knowledge domains (e.g. mechatronic systems). Therefore product development has to happen increasingly in cooperative networks. The individual subtasks that have to be treated need suitably structured requirements. However, the original customer needs must remain as the unaltered superior development goal. The customer generally is oriented to the whole product and the total costs during service life. For special products (e.g. parallel robots) apart from investment and operating costs particularly training, maintenance, reconfiguration and recycling are important. At the same time shorter product development time and lower costs are desired. How is it possible to shorten the way from customer query to the finished, operating product drastically? It is shown that within the area of parallel robots a flexible modular system and an effective requirement management will lead to a reduction of development time, a decrease of product costs and a better fulfillment of customer requirements and wishes.

2 Development of Parallel Robots

The collaborative research center „Robotic Systems for Handling and Assembly" (SFB 562) concentrates on the development of high dynamic parallel structures [13]. The focus of research is located in the area of high accelerations (~10 g) and velocities (~10 m/s) and at the same time high repeat accuracy (< 0,01 mm). Application areas are e.g. pick-and-place, handling and assembly tasks (assembly of small parts, assembly with high precision) at payloads up to 3 kg.

To reach these aims interdisciplinary teams are working e.g. within the areas of *concepts and modeling*, *control and information processing* and *new components*. To control the complexity of these new products while considering the requirements of present and future markets specific development methods were worked out.

Development can be divided into *new design* of a robot, *configuration* with (for the most part already designed) modules and *reconfiguration* of already operating robots.

2.1 New Design

For the new design of a parallel robot the following steps are necessary: A task generates requirements. Those are the basis for the structure synthesis. When a principle structure is found the kinematic analysis follows. Then a detailing of the structure and eventually the dynamic analysis takes place. The outcomes of the dynamic analysis can necessitate an iteration loop back to the detailing or even to the structure synthesis. Then the control engineering steps follow.

The development needs various knowledge domains (e.g. mechanics, production engineering). Specialists from different science disciplines must be involved, as well as a simple exchange of outcomes between different knowledge domains must be possible [3].

2.2 Configuration

Parallel robots are designed and optimized for special application areas. Within the application area of SFB 562 a flexible modular system can be used. Thus, different robots can be build from standardized parts in various configurations [12].

2.3 Reconfiguration

While in bigger enterprises with high lot sizes and chopping frequencies highly specialized and optimized machines can be used, smaller and medium sized enterprises can use the advantages of reconfigurable robots. Reconfiguration is a change of robot characteristics in operation [7]. The investment costs purchasing a robot for a current task are worth it, because there is a possibility to reconfigure the robot at relatively low costs for another task. *Static* and *dynamic* reconfigurations can be distinguished.

Static Reconfiguration

Static reconfiguration denotes a manual rebuilding of a structure. For instance, the arrangement of drives can be changed. However, a rebuilding to a complete new structure using the existing components is possible, too. After rebuilding, a new robot with new kinematic characteristics and a new work space is available (cp. Fig. 1).

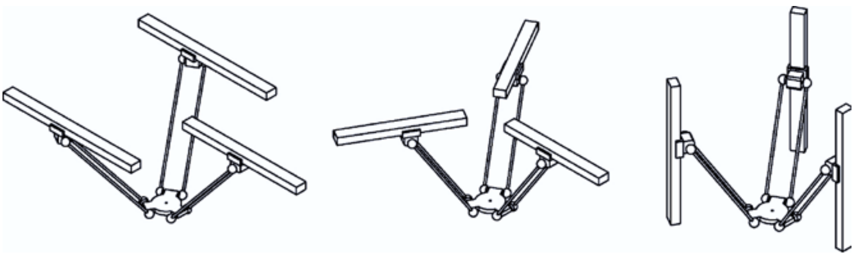

Fig. 1: Different possibilities to arrange the linear drives for static reconfiguration [13]

Dynamic Reconfiguration

Two types of dynamic reconfiguration can be distinguished. Type 1 uses the transition of singularities of 1^{st} and 2^{nd} order to generate an additional part of working space [1]. The set up of the structure remains the same. Type 2 uses the changing of kinematic characteristics in operation [4]. This employs e.g. rods variable in length or adaptive joints that can block one degree of freedom in operation [11].

2.4 Problem Fields

The effort of developing a complete modular system is much higher than a new design of a special product. If the complexity of the modular system should stay small a segmentation into few standardized elements is reasonable. Often Interfaces have to be oversized to connect smaller and bigger variants of a neighboring element. Higher costs are often overcompensated by economies of scale. Within the field of high dynamic parallel robots an oversize reduces the performance. A lower performance and thus higher cycle times lead to a lower productivity. A modular system for parallel robots must be flexible enough not to decrease the overall performance.

To guarantee the reconfigurability of a product the related requirements have to be considered already in the run-up phase. The demand on a modular system increases. Parts must be exchangeable. Furthermore, relations between requirements and parts must be known, i.e. if a requirement changes, relations and constraints must be available allowing the robot to be reconfigured in a reasonable way. For instance, if a better accuracy is demanded it can be appropriate to use better sensors and therefore reach a better calibration. Otherwise it can be appropriate to use adaptronic joints that can lower the clearance at working point.

3 Solution Approach

The approaches to solve the problems within the area of development of parallel robots are among other things the introduction of modular systems, an effective management of requirements and a useful data processing. The approaches are explained in the following.

3.1 Modular System for Parallel Robots

The modular system [12] standardizes the robot system into modules. This allows a fast configuration of different robot structures. The main advantages of solutions producible by a modular system are a shorter time-to-market (parts do not have to be newly constructed for every new task), bigger lot sizes for standardized parts (reduced intern variants) and thence economies of scale [6]. Furthermore costs of the robot system can be calculated faster and more reliable because detailed cost information is attached to standardized parts.

The robot is mostly configured out of existing parts. For special tasks single parts can be purposefully adapted or newly constructed. However, experience and basics can be reused. The concept of a „living“ modular system allows a successive extension, thence a steadily growing database.

The set-up in different levels of abstraction allows a high flexibility. Furthermore, it makes it possible to define work packages in early phases and provide information that can be used in different development departments. Moreover, superior modules can be divided in different ways according to the special knowledge domain. For instance, for a design engineer an adaptronic joint (module *joint*) consists mainly of housing, bearings, shaft and piezo element. For a control engineer the same joint consists of a control loop with various in- and outgoing variables.

Modules

With the developed modular system a structure can be built up out of 10 separate modules (e.g. joint, rod). It is known which modules are compatible and which not. The abstract structure plan represents the later robot and can be used for considerations in subsequent disciplines (e.g. control). Fig. 2 shows a hexa structure built up out of abstract modules. As a detail the modular spherical joint (combination of a cardan and a swivel joint) is shown.

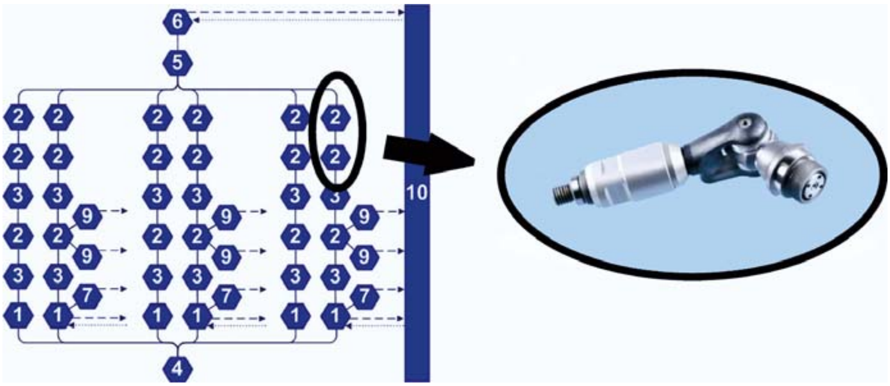

Fig. 2: Abstract structure plan of a hexa structure and joints used

Subelements

Often it is reasonable to fractionize modules into smaller subelements. This increases the flexibility of the structure. For instance, a module *rod* can be built up of a *basis* and two *adapters* at its ends. If the work space should be augmented it is sufficient to exchange the basis and keep the adapters. Furthermore it is possible to easily vary characteristics within a module. For instance, if the housing of a sensor at a cardan joint is a subelement it can be varied while other elements of the joint (e.g. bearings) remain the same.

3.2 Modular System for the Rack

Besides the robot structure the rack claims a big amount of development time and production costs. The concept of a modular system allows to treat the rack as an independent module as well as not to lose the reference to the superior product. Within the module *rack* a new modular system emerges that keeps its defined interfaces to the robot system.

The different types of reconfiguration demand different requirements on the rack. Demanded work spaces of dynamic reconfiguration are those of the different working configurations and also those of configurations that are necessary to change the configuration. Thus the rack should provide all these work spaces without being manually rebuilt.

Also the static reconfiguration (e.g. change of drive orientation) should take place without manually changing the arrangement of the rack. If the new structure is very different to the original structure a manual rebuilding of the rack is inevitable. (Fig. 3 shows two examples of racks for the different robot structures hexa and triglide.) To keep the cost low it is reasonable to reconfigure the rack, too. That means existing parts should be used, arranged newly and where necessary supplemented by new parts.

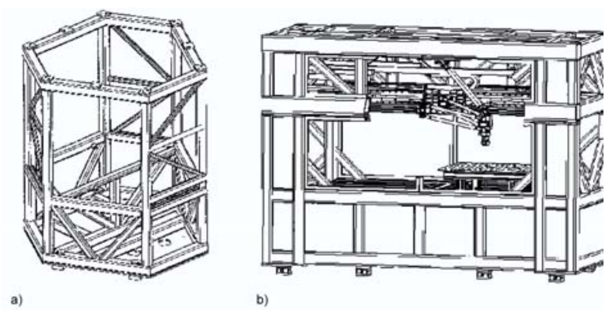

Fig. 3: Conventional racks of a a) hexa and a b) triglide structure [13]

3.3 Requirement Management

To guarantee a purposeful development and to deliver a product that meets the customer wishes a reasonable management of requirements is necessary, especially for complex products. Following the specific literature [8, 10] even for configurations with partly new constructions a full clarification of task is necessary. This statement can be extended to reconfigurations. If for a product detailed requirement lists and relations to product characteristics exist [2], a change of requirements leads to exact starting points for optimization or reconfiguration, respectively. For instance, an existing delta structure (3 DoF) should be used for a task with nearly the same work space but 6 DoF. The relation between DoF of the structure and number and DoF of the chains leads to the possibility to change the delta into a hexa structure. Then only three additional drives and three additional cranks are needed.

A number of requirements can be seen as general (within the field of parallel robots). Knowing the exact requirements parts can easily be choosen out of a database. For instance, if dynamic reconfiguration is required it makes sense to choose adaptronic joints that can be locked during operation [11]. Otherwise passive joints with high stiffness, low clearance and low costs [9] can be the better choice.

Fig. 4 shows an overview of the use of requirements for configuration of parallel robots. For clarity reasons just two levels of hierarchy (robot system and modules) are shown. Hierarchy level *robot system* has a coordinating position. Its requirements have a superior character and specify the customer wishes. Requirements related to the development do not interest the customer. For instance, a special structure generates specific requirements on modules (e.g. cranks of a hexa structure are loaded by bending). Theses are important for the subsequent design process but they are not discussed with the customer.

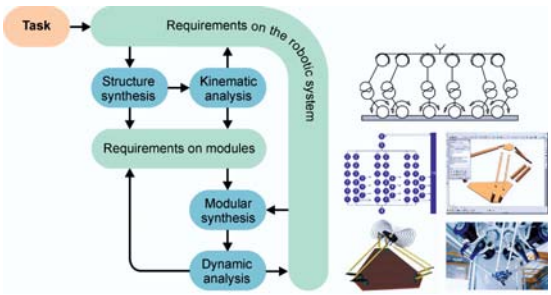

Fig. 4: Use of requirements for configuration of parallel robots

A structuring of requirements according to the purpose within the product development process is necessary. We can distinguish the type of design (new, variant, adaptation) and configuration, respectively. Moreover the phase within the development process (e.g. finding of effect principles, detailing) is a meaningful item for structuring. It results a system of structured requirement lists with different hierarchy levels and different detailing. Thus that requirement that is necessary and reasonable for one specific step of the development can be accessed at the right moment. For a pure configuration (i.e. choice of existing solutions for the modules) a requirement list has to be as detailed as possible. This allows a fast and reliable choice from catalogues. If innovative new constructions are demanded, requirements have to be formulated sufficiently open. That means the formulation of requirements must not preselect solutions. Requirements just give the scope and are specified iteratively during development. The finding of effect principles can be supported by effect catalogues. For an integrated management of requirements over the whole product development process it is important to know the relations. Primarily two types of relations are important: *relations between requirements* [8] and *relations between partial models* [5], e.g. requirement, structure, kinematic, dynamic, control or cost model.

Both types of relations influence each other. Hence a separate view limits the outcomes to qualitative statements. A *qualitative* estimate is possible when a specialist recognizes qualitative relations between requirements by his experience. Becoming more and more concrete the relations are to be based on physical principles. If relations were set too early in the design process and too intuitively (e.g. “Stiff things are always heavy.”) the finding of solutions is hindered (e.g. the detailing (e.g. ribbing) and choice of material is crucial for stiffness and weight).

Relations can be directed, e.g. between *big work space* and *low rack weight* exists a goal conflict (negative relation). The additional positive relation between *low rack weight* and *low rack costs* leads to another qualitative (negative) relation between *big work space* and *low rack costs*. Another example: The *repeat accuracy* is related to the *robot stiffness*. The *robot stiffness* is related to the *rod stiffness*. The *stiffness* and the *mass* of a rod have a qualitative relation. Thus, between *repeat accuracy* and *mass of a rod* a relation or constraint exists, respectively. Such (indirect) relations are important to effectively optimize the structure. They can be found automated e.g. with a software tool. Nevertheless the plausibility of indirect relations is to be proved because not necessarily all relations and particularly not quantitative dependencies are shown. An uncritical adoption can lead to wrong decisions.

If relations between partial models are defined simultaneously the relations between requirements can be defined more concretely. Inter-model relations between the requirement and structure model lead e.g. to physical true dependencies. If reliable inter-model relations between requirement and cost model are defined a robot can be built up that fulfils the cost performance ratio demanded by the customer. For instance, expensive sensors are only used if this leads to a cheaper total system or if otherwise the demanded accuracy cannot be met. Moreover, it is possible to make an early estimation of what the fulfillment of a specific requirement will cost.

4 Conclusion and Outlook

Approaches were shown to face the increasing cost pressure, the decreasing product development time and demanded flexibility. One promising approach is the use of flexible modular systems that support configuration and reconfiguration as well as adaptation and variation of existing solutions.

A second approach is the improved handling of requirements. Very important is a suitable structuring of requirements for the different phases of design process. A continuative approach is the modeling of inter-model relations.

5 Acknowledgements

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A Scandinavian Model of Innovative Product Development

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Abstract
The educational systems in the small Scandinavian countries are open to experiments and new education programmes. This paper presents such an initiative from Denmark, showing new interpretations of industrial needs, research insights, educational ideas and identification of core innovative competencies. We reflect on our efforts to produce a new type of design professionalism, pointing to new roles and identities for the professionalism of synthesis and innovation. Finally, we round up by articulating what we see as the future pattern of product development, which should be supported already today in our education programmes.

Keywords
Innovation in Product Development, Design and Innovation, Engineering Education

1 Industrial Situations and Politics

It is recognised that Scandinavian countries maintain a high standard of living and a strong position on the world market, based upon knowledge-based innovations. Many branches and initiatives are contributing to this, including of course those based upon engineering. Traditional views of engineering as the supplier of technology, and of technological insight as the driver for industrial power, force design institutions to increase their efforts to avoid marginalisation. At the same time industrialists warn about too little focus on product development competencies in industry.

When innovation is measured and compared in European countries [4], Denmark is in the best end concerning innovation, before UK, Germany, France and Italy, but with regard to dynamics, Denmark is behind Ger-many.

When it comes to research and education Denmark is in third posi-tion after Finland and Sweden, but the high position is mainly due to life-long education. Sweden has the highest position, together with Finland, concerning innovation and Finland has the highest position concerning dy-namics and education – closely followed by Sweden.

So one may ask oneself whether the situation in the Nordic countries is not a perfect one? The forces creating these results are not easy to identify, even if there are of course core influences from industrially leading companies. But other contributions come from new, innovative one-of-a-kind businesses. There is no doubt that the society's welfare and standard of living cannot be maintained without efforts on an industrial scale and based upon industrial insight. We can therefore expect that engineers of any kind will be important actors in this innovation effort.

Danish industrialists point out that the importance of product development and innovation in industry is strongly growing, but the focus upon the way we are working is weakening. What are the industrial policies in Denmark for long term survival in the global economy?

Denmark was traditionally a farming society which entered onto the industrial scene relatively late, except for some remarkable exceptions like ship building and diesel engine development. It is characteristic that Denmark has only implicitly articulated industrial policies, and the goals for the use of education and research as a means for industrial enhancement only stems from political and not industrial sources. For a period the 'service society' was seen as the mantra. Today there is a strong polarisation between technology-based innovation, focusing on internationally competing world class universities and research, – and user-driven innovation, where industrial designers, anthropologists, socio-technical researchers and other humanistic professions are seen as the main actors. At the same time Denmark is nursing innovationists on small scale, by means of sparse financial support.

Characteristic for Denmark – and for Europe in general – we are experiencing a reconfiguration of economies, driven by a series of factors, which when gathered together are recognised as globalisation. These factors include: the development and industrialisation of Eastern countries; the advancement of ICT; the opening of political, cultural and trade borders; the increasingly high living standard (and thus cost of living and labour) in the western world; and so on. The industrial arena in Scandinavia is therefore undergoing significant changes as companies face a number of major strategic decisions: outsourcing or insourcing; own development or innovation based on acquisition; local or global product development projects; etc. There is no doubt that companies simply must act quickly and in an agile manner, in order to stay one step ahead of pending competition. Thus far, many companies have had little time to consider a strong dialogue with the research community regarding their actions and the subsequent effects on their product development processes.

On the other hand these groundbreaking moves by internationally operating organisations are creating quite uncharted situations for product development and product developers as such. The lesson of *integration* from Integrated Product Development [2] is still valid when we consider the integration of capabilities, expertise and diverse cultural insights, but it no longer holds true when we consider the physical organisation of product development (collocation, one-site development/manufacturing operations, etc.). The product development task has become much more complex – due to complex products, an exponential increase in the number of stakeholders involved, etc. Markets are broader and much more varied. Manufacturing possibilities are much greater but also much more spread. And the whole issue of communication in product development is a great challenge for companies [8]. There is therefore an urgent need for western countries to receive a revolutionary influx of new competencies through their engineers, in order to be able to live up to the many challenges that the new global industrial arena brings with it.

2 Traits of the Educational System

The Nordic countries are characterised by a relatively high number of technical universities, especially after new legislation, which has forced engineering schools into the academic system.

The political climate in Denmark is characterised by detailed control as the means for creating better quality and efficiency, – and a focusing of higher investments into education and research in deep technical silos – with little or no focus on the bridging, synthesis-oriented competencies. The slogan from the government's side: "From idea to invoice" is a dream about a financial utilisation of researchers' ideas. Unfortunately, neither the government nor the universities have a track record with this professional side, nor the necessity of research efforts related to product development to facilitate innovation.

The area *design & innovation* in technical education has two origins; one related to business schools, and one which had its origins in mechanical engineering (similar to most European countries). At the Technical University of Denmark (DTU) topics, specialisations and a chair of engineering design have existed since the early 60'ies, based upon traditional mechanical engineering courses, but focusing on engineering design and product development. Over the years these activities have established a distinct articulated teaching programme for engineering design and product development; the latest development being an entirely new Masters programme, *Design & Innovation*. As we describe in the following text, this new programme aims broader than traditional mechanical engineering.

It is an interesting fact that the technical disciplines outside mechanical engineering have only sparsely developed traditions for research into the process and organisational patterns which create new products, processes and service. Therefore, it is only partially recognised that the area of product development is teachable and supportable by research, even if a technical university ought to see this area as a supporting area for the university's core effort to serve industry.

3 Industrial Challenges and Needs for Product Development

The engineers we educate today will hold large responsibilities for tasks in companies; this distinguishes them greatly from traditional engineering education. We believe the new pattern has the following characteristics:

- enhanced quality efforts.
- customer-oriented quality, values and perceptions.
- environmental concerns and demand for sustainable solutions.
- exploding design complexity due to technologies, multi-product development, customisation, legislation and product life concerns.
- mass customisation, multi-product development, platform thinking.
- multi-disciplinary product conceptualisation.
- globalisation of markets, supply, technology and customers.
- necessary dynamic innovation of products and organisations.
- handling of knowledge and competences [3].

Besides these challenges there are several 'old virtues' of specific importance for product development, which may be seen as competences for product developers, project leaders, and product development managers:

- organising design: structures, processes, tasks, milestones, etc.
- understanding product development types: innovation, development, variants, configuration, re-use, etc.
- managing integration of product-life concerns and multi-disciplinary work patterns.
- utilising diverse knowledge & skills in a product development team [8].

From our dialogue with Danish companies we can also derive an important set of criteria for professional product developers. These include: the ability to synthesise (creative ability); to visualise and communicate; to stage the design process (design of design [3]); to utilise knowledge and skills in related subjects and areas; to utilise and lead specialists in related subjects and areas; and to function well in, or lead, a design team.

4 The Influence from Research on Design in Industry

Designing is not the same as engineering, but is normally based upon the same basic education. Science approaches are very influential on engineering, but are they supportive for design? Socio-technical research tells us how to understand practice, new science how to operate and evaluate in practice [6].

The paradox of engineering education [7] is that the fit to industrial practice is so poor: Most engineers rarely use formal theory or methods explicitly, engineers experience 'application-fright' and de-/re-learning is a necessary activity when the fresh candidate enters into industry. Two tendencies are apparent: Engineering education is fitted to industry to such a degree that engineers have become the 'house maids' of industry. Furthermore the 'scientification' of engineering has made research universities dominant and given natural science a dominant role [7].

Is it true that science and research are the origins of technical development and the core of engineering knowledge? Have we made insight into the human activity of designing (which can hardly be explained by engineers) into a marginal area? Research into these questions shows that the process of making technology disciplines scientific has made engineering less creative and innovative [12], and that design activities and other 'soft' elements of engineering knowledge have lost their importance.

What does research tell us to do? First of all we must be aware of the translation and transformation of insight, which characterises the transformation from novice to expert. Through this activity, experts develop cognitive maps and implicit routines [11]. For education and practice it is important to learn to solve complex, authentic and contextualised problems, instead of the 'ritual' problems of science. Socio-technical science points out that engineering is a heterogeneous activity, combining several routines and disciplines into a *community of practice*. Designing is to a much higher degree a question of competences than knowledge, where competences may be seen as the ability to combine knowledge, experience and contextual reflections in problem solving under organisational and other constraints [10].

5 Educational Concepts for Innovation

The following terms characterise and underpin our key educational basis for training future innovative engineers. "*Innovation* concerns the search for and the discovery, experimentation, development, initiative, and adaption of new products, new processes and new organisational set-ups" [9].

Product development consists of projects often beginning with the perception of a need and a market opportunity and ending with production, sales, delivery and servicing of the product. But beside this product development is found in the company's business plans, connecting business-, technology- and product strategies, and in the product planning and portfolio management.

In Scandinavia the word *design* is taken from the English language but normally understood as *industrial design* (form-giving), concerning the area of product-related activities, based upon artistic efforts. It is our attempt to create a broader meaning of the word *design*, concerning areas such as:

- architectural design,
- industrial design,
- engineering design,
- system design,
- product/service design,
- holistic design.

Our arguments are that no clear distinction between these areas can be made, and that a single product's development often demands a number of these areas' involvement at any one time. The areas may rather be seen as educational accentualities than types of designing. There are several efforts in Scandinavia to create education programmes that merge industrial design and engineering, focusing on industrially produced products.

Within DTU's new education programme *Design & Innovation* we create *Design Engineers*. We have gathered our inspiration for the development of this programme from (i) the insightful companies and industrial colleagues who are close to us and bold enough to formulate their needs; and (ii) the growing body of interest from educators/researchers in this area. Our mission is to educate engineers who are able to identify, formulate and solve problems that arise in the context of application – as opposed to merely being able to solve problems that can be spotted within a narrower and well-defined discipline [6]. Or in other words, we are not merely creating designers as executants, but also designers as enablers, planners, differentiators and scene-setters, as Heskett differentiates [5].

6 Initiating Change

In 2000 a series of concerns were being raised, regarding falling student numbers – especially amongst the mechanical engineering students – and a general lack of applicability of the capabilities of engineering candidates in industry. Ten colleagues from two departments at DTU created a strategic working group, with the mission of creating a new agenda for design & innovation at DTU [1].

This agenda was presented to DTU's direction, together with a recommendation that a new education programme be formed, entitled *'Design & Innovation'*. After a series of efforts and our own detailed synthesis work, a new five-year Bachelor-Masters programme was formulated and launched in 2002. The key characteristics of this programme are:

- project-based syllabus (one project in each semester),
- thematic approach to learning (core themes such as workspace, ecodesign, etc. built in as 'red threads' throughout the syllabus),
- subject-integration (across and within subjects),
- steady dosing of foundation courses (as opposed to the traditional system of 1½ years foundation course first, before the thematic courses),
- strong emphasis on groups and team dynamics (contra a traditional, modularised and therefore individualised study programme),
- the creation of three specialisations in the masters degree: product innovation, innovation management, or systems innovation,
- a direct effort to nurture an industrial relationship for each student in the masters specialisation.

6.1 Three Core Competencies

We make no secret of the fact that we are educating students with a focus on three core competence areas in our education programme:

- *Technical engineering competencies*
  Reflective, technological engineering competences, which refer to the reform of teaching and integration of the core engineering curriculum.
- *Socio-technical competencies*
  Competencies to be utilised in the creation and renewal of systems and situations and where complex, political decisions confront the engineering field's way of modelling and optimisation.

- *Creative/synthesis competencies*
  Aimed at integrating technical and social components during the development of products, systems, processes and services. The education emphasises the development of the students' personal, creative potential, engagement and enthusiasm, professional insight and the mastery of methods.

These competencies are fundamentally built into the programme structure, the project work, the specialisations, individual courses, and – most importantly – the teaching staff!

7 Models of Future Innovation Product Development

Based upon our teaching experiences, our dialogue with companies and our tracking of literature in the area (from the worlds of business, engineering and the popular press), we forecast that future product development will be based upon a set of characteristics, outline below:

- global activities, spread in time, place and culture,
- a pairing activity, between technology- and market (user)-based,
- built on individuals' abilities to act in teams, to network on many levels of organisations and in society,
- with a responsibility for self, company, society (Corporate Social Responsibility) and within the boundaries of sustainable development,
- based upon understanding of the life-cycle – not the product,
- coupled with service as the main deliverable,
- with engineers being allowed into the decision process and development suite, only if they can prove themselves to understand context, complexity and business potential of their and other colleagues' actions.

We believe that our education programme has begun to address many of the activities mentioned above, but that there are a great deal of steps that we need to take in order to approach the above-outlined model in a more proactive and professional manner; both in our education and our research.

8 Conclusion

Although the education programme described in this paper is so new that we have not yet produced any finished candidates on to the job market, we allow ourselves to conclude our paper with the following statements.

The western world needs new engineering competencies in order to remain competitive, to retain a high standard of living and to realise how to constantly improve the social and environmental welfare of our society. Our education programme aims no lower than at these goals. Education concepts need to develop, to get old and be replaced, and to be criticised by the future employers of the candidates. We dare to say that any education programme in this domain that is *not* subject to these conditions is slowly dying – or ought to die!Engineering must focus on real business – also in education – in Scandinavia we need both the deep-divers, the orchestrators, the leaders and the stars that Heskett describes [5].

Talking, thinking and acting in competencies rather than skills is instrumental in this type of education activity. We can see already when our students carry out their projects with and for companies, that they apply their *knowledge*, their *skills* and their *attitudes* – which we believe demonstrates competency. As researchers and educators, we have a responsibility to foresee and develop models, methods and new development arenas for innovation, and to ensure that the candidates we produce are ready for the new challenges that will await them in industry in the future. Here our focus on competencies is important for us. Skills alone cannot prepare engineers for future activities, global collaborations, legislatory demands or business goals. But by training awareness, mindset and an ability to think in complex systems, we can equip our candidates with the means to be flexible and innovative. We must, as educators, think of the many roles of our students in the future and help them to fulfil these, before we let them loose. Team-working, role-playing, paper-writing/-reading, model building, calculating. All of these activities – and a host of others – create professional readiness. We believe that our vision to create enthusiasm, holism and a creative way of developing new business is bearing fruit – not only within the walls of the university but already within the initiatives established on the basis of the programme, and through the contact to the industrial world. Companies are embracing the students through project work and are showing great interest in the way in which we are educating the next generation of innovative product developers.

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Toward a Framework for Effective Collaborative Product Development

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Abstract
Collaborative product design is an approach for supporting designers connected by network, to participate in distributed and dynamic product development environment. Communication, negotiation, coordination and cooperation became essential for effective preparation and to follow-up design changes and conflicts. A collaborative environment requires a mechanism allowing the project actors to recognize and to resolve the interdependence-conflict among their respective terms. We suggest the use of constraint based system to facilitate and support the conflict resolution through synchronization process. This paper presents: (1) a framework to improve asynchronous as well as synchronous collaboration (2) a constraint based model for detecting design conflicts (3) a new notification mechanism for presenting conflict to all corresponding actors. These results should contribute to the improvement of collaborative design.

Keywords
Collaborative Design, Constraint Based Model, Synchronization, Conflict Resolution, Notification System

1 Introduction

Product development organization became an increasingly collaborative and distributed activity [9]. The collaboration within team members, working on a distributed product development environment requires a detailed study of integration and collaboration of the expert tools. Multiple tools and multi-view [13] representations in these environments allow designers to work together at different levels of product development process. Collaborative product design environment requires the various design systems to provide coherence support among different models in design process which can be provided by three types of tool: 1) Shared space system with common model [7], which integrates PLM models and tools 2) Versioning system [6], which allows alternative designs to be created and design modifications to be tracked. 3) Notification and synchronization system, which detects inconsistencies or conflicts among models and also provides configuration support allowing actors to monitor, configure and resolve their environment's inconsistency and conflicts [2]. Such dynamic environment requires more active functions for model structures and relationships of design objects and handles design constraints as design specification. Here, we discuss constraint management [5, 10] as an issue to achieve a dynamic model providing functionalities of notifications to follow the evolution of the shared model. Constraint management includes constraint definition, constraint verification and notification mechanism in case of a constraint violation event. After discussion about existing collaborative design environments, we discuss a range of existing constraints [4] in collaborative product development process which can be used to address inconsistency measurement issues. We describe our inconsistency management model, the system architecture that realizes this model, notification approaches to the presentation of inconsistency during collaborative product development, and synchronization systems which describe how actors can use such presentations to monitor and resolve conflict problems.

2 Collaborative Design Environments

The design of product is a complex process that usually involves collaboration between actors from different disciplines who often work in distributed environment and do not use the same description for the same object. The related approach to manage this complexity is the integrated product design which facilitates collaborative design environments. It supports multiple tools, and multi-view editing in these environments which in turn allow developers to work with design components at different levels of abstraction, using different representations [7]. As illustrated in Fig.1, there are two major approaches for designers to share and exchange integrated design information. The first approach (fig. 1-a) is the direct exchange of information [8]. With the direct exchange approach, designer applications should be aware of each other's existence and communication channels must be established between related designer applications. With this approach, the number of communication channels needed grow with the number of designer applications. The second approach is indirect (Fig. 1.b & 1.c), generally involving a Shared Model server, in which all the designer applications is integrated into a single system. Support for Shared Model server collaboration can be provided by two types of tools:

a) Synchronous control tools, which allow concurrent manipulation of a system by two or more designers. During synchronous collaboration, developers share the unique view represent by the shared model. Changes made by one developer are reflected in the view of other related developers (fig.1.b).

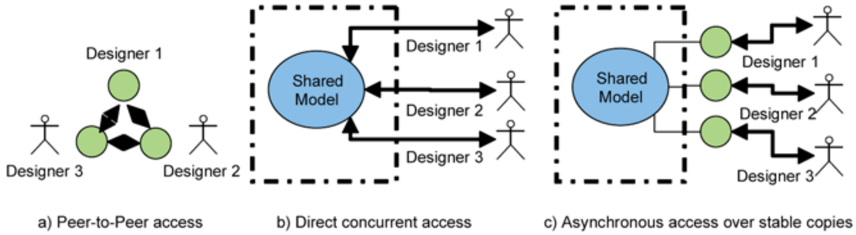

Fig. 1: Information access framework

b) Version control tools [6], which allow alternative designs to be created via different copies and to be merged asynchronously. In asynchronous access framework, designers should copy a part of the shared model into a private space in order to get a stable version of information during their design job (Fig.1.c).

One of the issues that appear in most shared model design systems is the inability to automatically track all the impacts of a design change. Hence, an effective approach to track the design changes is needed to improve the collaborative design process.

3 Inconsistency in Multi-view Environment

In shared model collaborative design, actors work independently, modifying alternative versions of views. Any inconsistencies and conflicts generated require tracking and then negotiation and resolution which are usually done during synchronization between different versions. Thus, modifying the entity of a specific view in one tool introduces inconsistencies with related entities of other views specified in others tools. This may be:

- between the same view (single view consistency)
- between the different view (multi-view consistency), (Fig. 2). In a collaborative design system, experts are very often misinformed of the beginning, or existence, of such inconsistencies.

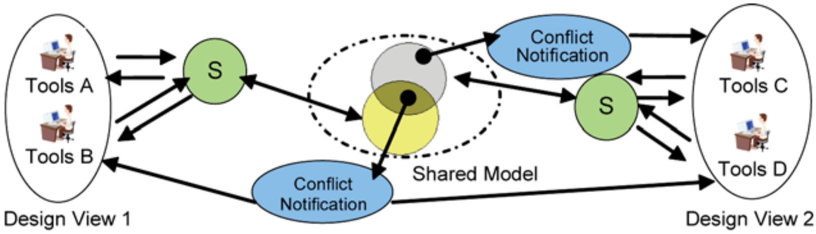

Fig. 2: Conflict detection issues in multi-view environment

Some conflicts could be automatically corrected by tools updating the information in one view when another, related view has been edited. However, many conflicts cannot be automatically corrected. Hence mechanisms are required for tools to detect and evaluate conflicts in order to notify concerning actors. Actors require conflict monitoring, tracking and resolving facilities. Diverse research efforts were provided about change and conflict notification in database systems area such as active database systems [15] and distributed database systems [9]. Usually, active database systems make use of the Event-Condition-Action rule architecture, in which an event triggers a rule and then related actions are performed if the condition is satisfied. Because of the complexity of design environment, the big heterogeneity of design tools and the lack of interoperability between design tools, there have been no researches that apply these active database concepts to the shared model management area for supporting collaborative design.

4 Constraint based Collaborative Product Development

We assume that the management of inconsistency and conflicts could be improved if the integrated design system would use a real time conflict detection system in order to detect structural or semantic conflict between different views. A key aspect is to analyze the impact of one entity modification on other entities. Explicit relations are directly deduced from the entity relationships integrated in the shared model. Nevertheless more complex links should be undertaken. Many models formalize these links through identification of constraints as design specifications. If we consider design process as a network of constraints and relations among the design entities, conflicts, can then be seen as violated constraints in the design problem being solved in a collaborative approach. Our proposed conflict notification mechanism could be used to apply the active database concepts with user defined constraint into the collaborative shared model management systems (Fig. 3.a). In this approach, designer should copy a dependent part of the shared model to their private space. An internal copy change is not directly reported into the common shared model: a notification is sent to every person concerned by the edited entity. We call this scheme an anticipated notification scheme [2] because the notification informs collaborators that there are conflicts between edited copy model and shared model before the designer request a modification of the shared model. Every designer can continue his job with a stable external model copy but he loses the connection with private user and shared model space and would not be informed about trends and where conflicts may occur. Check out procedure is later applied to transfer the modification results to private user space (internal copy) and constraint propagator will be activated to detect the modifications (Fig. 3.b)

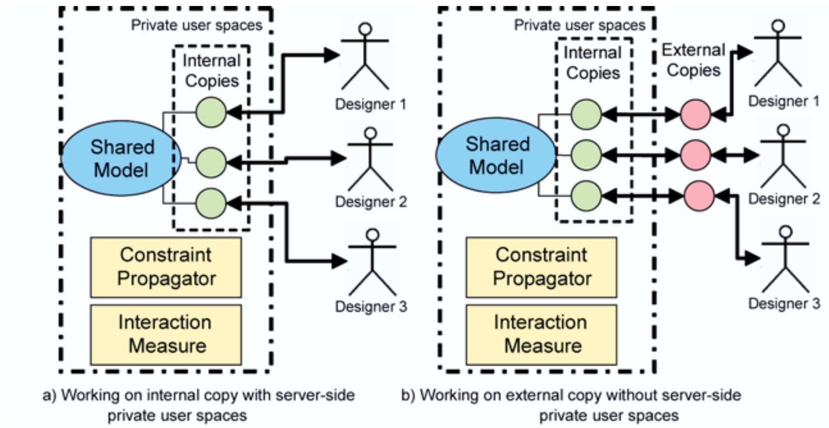

Fig. 3: Collaborative framework for anticipated notification

Main models are based on ECA (Event Condition Action) representation: as soon as an event occurs over an entity under certain conditions, an action is automatically executed propagating new events. In some cases agent policies may be used to automatically answer to events. Since some actions are not automated, human may be involved in the constraint propagation by notification procedures.

5 Conflict Handling and Notification System Requirements

We outline conflict handling and notification system requirements through an example of collaborative design of a dough mixer machine (Fig. 4.a). When Expert 2 edits his version of the view, changes are propagated to shared model environment. He can also generate constraints among the entities of the design. Conflicts introduced by modifications done by Expert 2 are detected in constraint management system. They must be detected when constraints associated with modified view structures are violated in some way. Experts require facilities to configure when and how conflicts should be detected, monitored, stored, presented, and possibly automatically resolved (Fig. 4.b). Methods are needed to check violated constraints and represent the relative importance of conflicts and record them for monitoring and later resolution. The system could select notification strategy according to conflict representation. The choice of notification strategy often depends on how experts can most appropriately be informed of the presence of different kinds of conflicts. For example, conflicts which need quick resolution to allow design process to be preceded should be immediately presented so that experts act upon them. Conflicts which do not have a large impact on the information displayed in a view should be highlighted only when requested by experts.

Expert 2 needs to interact with conflict presentations to locate their causes, gain more information about them and resolve them. He also requires support for negotiating the resolution of conflicts presented with Expert 1.

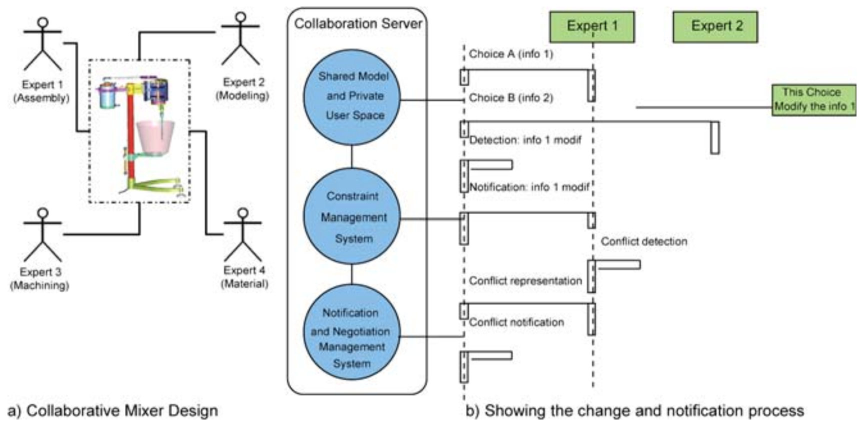

Fig. 4: Conflict handling and notification system

We currently use the PPO shared model issued from the IPPOP [3] project to implement the proposed framework. The PPO model integrates product, process and organization concepts to deal with every design views. The method we describe in this paper is based on the declaration and checking of constraint network defined on a collaborative design shared model in order to check its consistency. So, constraint definition and classification are the key issues for this framework. Constraints in a collaborative design process can be simply classified into constraints inside each kind of entity model and constraints between different kinds of entity models according to product, process and organization view of design (Fig. 5.a):

- **Product/Product constraint** that represents relationships between entities defined by product model. For example, constraints about dimension, geometry, tolerance, etc.
- **Process/Process constraint** that represents relationships between entities defined by process model. For example, resource constraints of task
- **Organization/Organization constraint** that represent relationships between entities defined by organization model. For example, decision making constraints in organization units.
- **Product/process Constraint**: such as constraint about which parts are operated by task x
- **Process/organization Constraint:** for example, constraint about choice of responsible for task x.
- **Product/ organization constraint**

Such classifications help choosing the right constraint management system which produces and maintains constraint definition, evaluation and resolution methods. In every context depicted in fig. 5.a, the constraint management systems to be considered in collaborative design framework are mainly dependent on constraint/entity position in the 3D space presented in Fig. 5.b:

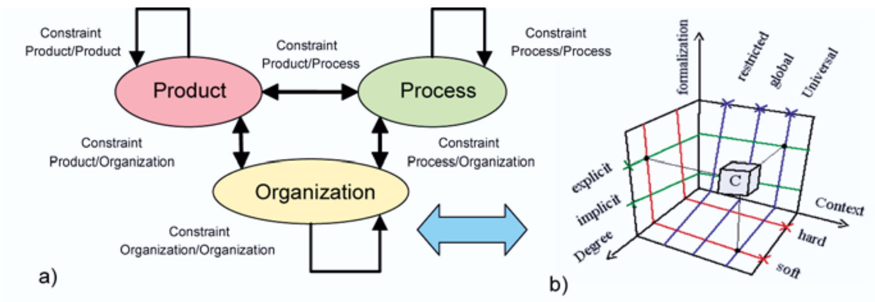

Fig. 5: To valuate constraint importance

a) **The "Context"** axis refers the groups of people which should be interested in this part of the product. As a result of collaborative design and resultant hierarchical shared model architecture that separates private and shared design workspace, constraint can be divided into three categories: local constraints impact the entities in one workspace view design, global constraints are represented between entities in different views. Universal constraints impact every view and designer. This separation provides the facilities for constraint changes and verification management in a distributed design environment.
b) **The "formalization"** axis identifies the degree of formalization. It is an indicator of the methods that are used in constraint definition, evaluation and resolution. Constraint may be implicit and requires to be evaluated on a fuzzy mode by designers; constraints are explicit when mathematics rules could be applied. They are expressed declaratively in some specific language.
c) **The "degree"** axis identifies the priority, violation and dependence degree of constraints in conflict handling process. The hard constraint must hold for all solutions, while the soft constraints should be satisfied if possible. These three criteria must be used to define the constraint importance in notification message.

6 System Architecture and Operation

Architecture to encode the anticipated notification framework is described in Fig. 6. Each expert can be connected by special API (Application Programming Interface) to the shared model space (Multi-view space) and constraint management system. Shared Model space is connected to constraint management system by configuration system. The constraint management system provides a constraint manipulation interface that allows the definition of constraint according to the configuration system parameters. In addition, with definition of constraint classes, the system provides the suitable constraint verification and conflict notification methods. Configuration system is used to define the design view classes, user classes, constraint classes and relationships between them. It allows specifying what constraint representation approach (formulation, degree and context) is possible for each design view class.

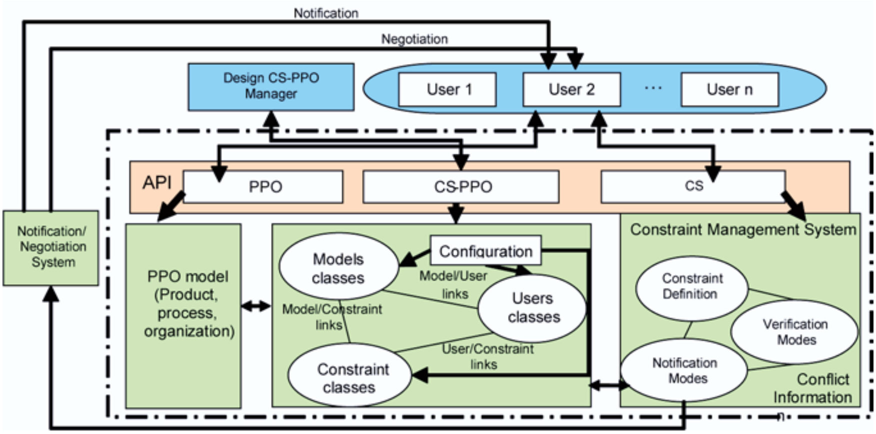

Fig. 6: Architecture of constraint based collaborative design

Figure 7 shows the system operation. Once the collaborative shared server is in operation, ECA rules provides the change detection (even) mechanism in the shared model environment. Change detection is normally associated with a design view modification in private user space, when a change in entity structures or values directly affects the consistent state of the Shared Model. Relevant models and relationships are determined for each modification. It is necessary to verify all of the concerned constraints. According to constraint categories, system should provide corresponding constraint verification and propagation approach. If every concerned constraint remains valid, the modification should be fully accepted. However if system detects a constraint violation, it will proceed with the violated constraint resolving plan and every concerned designer should be notified about the modification.

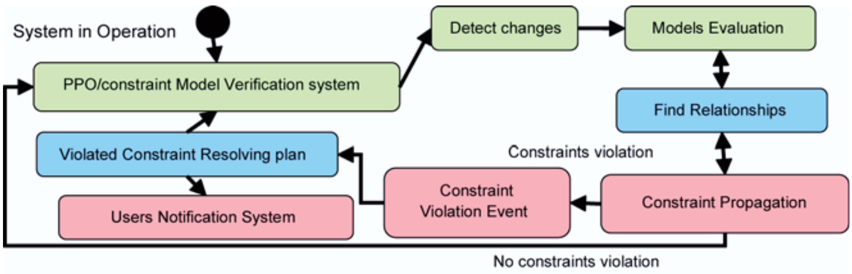

Fig. 7: System Operation

7 Conclusions and Future Work

In this paper we presented a collaborative design framework architecture that allows the definition and verification of constraints to assist design conflict resolution strategy through the synchronization and negotiation process. This assistance requires many new tools to be specified, developed and validated.

We discussed the structure, mechanisms and implementation of the notification concept which allows the detection and the management of conflicts in a shared model collaborative environment.

In order to complete this initial research, our future work would deal with development and integration of constraint management system which are specific to different constraint definition, evaluation and resolution methods. Simple use cases should be implemented, like the design of the dough mixer machine, to validate this approach.

The authors were involved in the IPPOP project which mainly proposes a static Product Process Organization model dedicated to collaborative design. We currently use this model to implement the proposed framework and to validate its pertinence.

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Scalable Product Development in a Collaborative Environment

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Abstract
The pioneer product concept is a product creation concept which focuses on consequent reuse of existing and approved product components and partner networks. At the same time the concept is clearly focused on the differentiating and customer relevant product features. The main objectives of the pioneer product concept are reduced project lead time, cost and risk as well as improved project reliability. Those objectives are facilitated by several distinctive capabilities relevant for the pioneer product concept: cross functional teams, customer orientation, cost orientation, partner collaboration and process orientation.

Keywords
Product Development Process, Pioneer Product Concept

1 Introduction

An increasing numbers of product variants in ever shorter time impose a tremendous challenge to the internal product creation processes. Among other challenges, coordinating the interactions among the involved stakeholders and managing the numerous variants make product development an increasing collaborative endeavor.

The fulfillment of changing requirements from stakeholders, such as customers, partners and internal functions, is a challenging venture and concepts to handle it are often not well understood. The main focus of our research is to understand how industrial companies can derive competitive advantage from scalable product development. Thinking in options in fulfilling stakeholder requirements in a R&D context in order to reduce the risk of failure is an interesting approach and has been discussed before [4, 17, 19]. Most of these approaches which regard flexibility and information improvement as a means of reducing the failure rate of new products mainly focus on the customer interface of R&D [4, 17, 25]. Hence, most approaches lack an integrated understanding of the complex resource and information flows between the involved stakeholders. A resource-based view integrating different perspectives of involved stakeholders is a promising approach [cf. 3, 6].

In order to reduce the risk of new product failure the **concept of pioneer products** has been developed to support the understanding of the complex interactions between the involved stakeholders in R&D and to support flexible decision making (cf. Fig. 1). The concept of pioneer products is supposed to enrich available market, product development, production and supply chain information and hence to provide an opportunity to make informed decisions based on integrated understanding of the stakeholders.

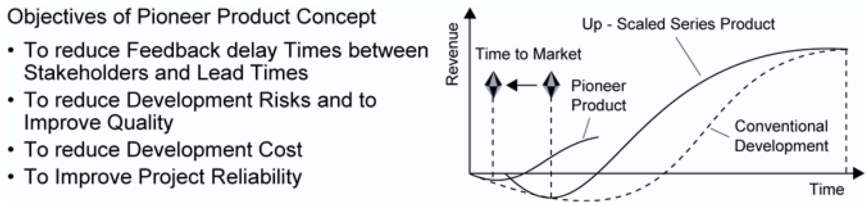

Fig. 1: The pioneer product concept

2 Research Approach and Empirical Findings

2.1 Resource based View as a Framework

Streams of literature comprise the resource based view of the company and its derivatives like the knowledge-based view, company strategic capabilities and interface management [1, 10]. The resource based view tends to be process orientated and focuses on learning [7] and transferring resources and information [16] in order to apply it to specific situations and generate valuable knowledge. Interface management, resource and information flows between involved stakeholders taking the knowledge asymmetry within and outside the company into account are important aspects of the pioneer product concept.

2.2 Empirical Findings on Pioneer Products

Our investigations are based on an international survey of 134 participating companies from the equipment industry. The main focus of our research is to understand how industrial companies can derive competitive advantage from the pioneer product concept. In particular customer collaboration, modular product architecture, design for manufacturability and strategic partner collaboration have been ranked by the cooperating companies between 0 (capability not existent) and 4 (very high level of command of particular capability). Project reliability is used as a success metric defining reliable companies with project reliabilities above 72% and unreliable ones with project reliabilities less than 56%. Differences in the evaluation of capabilities are evident in customer collaboration (3.1 vs. 2.4) and design for manufacturability (3.1 vs. 2.5) between reliable and unreliable companies. Differences are very low for strategic partner collaboration (2.2 vs. 2.0). It appears that the company-wide existence of cross-functional teams (3,4 vs. 2,6) supports project reliability. The results seem to support the hypothesis that differences in project execution correlate with certain important capabilities. These capabilities have in common that they are situated at the interfaces of functions corresponding with the quality of resource flows to and from adjacent stakeholders.

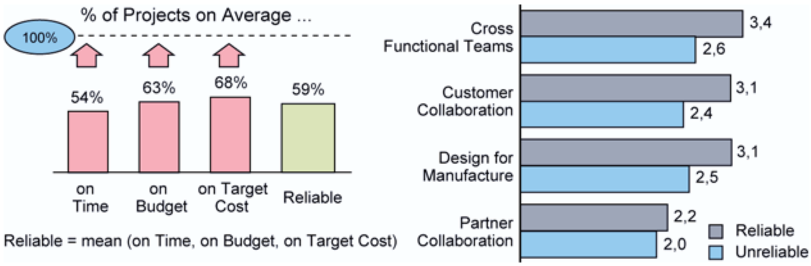

Fig. 2: Differences in the level of command of particular capabilities

3 Types of Pioneer Product Projects

It is useful for the pioneer product concept to arrange the variety of development projects into a typology in order to narrow the examination subject. The three investigated project types have a clear focus on cross-functional collaboration to support the overall project objectives.

Four specifications are defined to describe the degree of innovation. An incremental innovation is described by existing products, which are only changed to a minor degree [20]. If only a few components are changed and the interfaces remain conserved, the new product can be defined as a modular innovation [8]. An architectural innovation changes only the connections between several product components, whereas a radical innovation depends on new technical and scientific principles [23].

Customer integration determines the interaction with the customer [9] and ranges in a continuum between generic development and customer driven development [27]. Between the two extremes two more specifications can be distinguished: the target group development [24]. and the lead-user development [24].

The characteristics for the second portfolio lead time concept and type of production describe the internal view and support further classification of the pioneer product concept. The lead time concept describes the configuration of the development process and can be directly influenced by the company affecting time to market. Serial development, simultaneous development and rapid development are the chosen specifications distinguishing the lead time concept [5, 12]. Type of production on the other hand measures the lot size and can be categorized by the specifications single part production, small series production and series production.

Within the resulting two portfolios, three project types of the pioneer product concept can be distinguished (cf. Fig. 3). Radical innovations, intense customer driven development, single part production and serial development are not within the scope of the pioneer product concept because these four specifications would not release the full potential of the pioneer product concept.

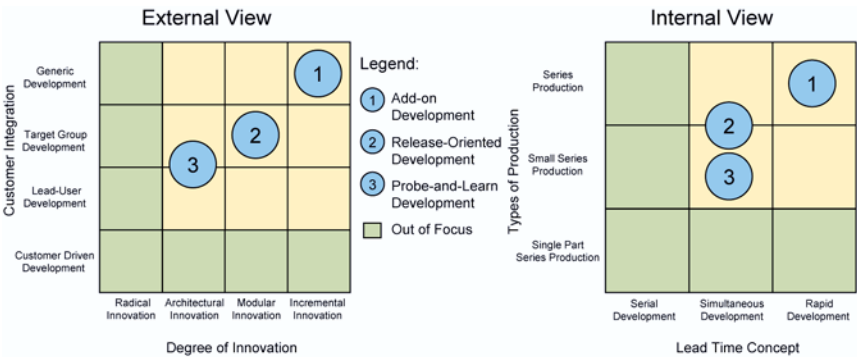

Fig. 3: Types of pioneer product projects from external and internal perspective

The project type **"probe-and-learn development"** is suited for products with a high degree of innovation, which are developed with lead-users and usually aim for a specific target group [14]. Innovations are generated by a combination of existing and newly deployed product technologies. The architecture of the new product usually differs from the initial model as a result of the new technology configuration. Hence, the degree of innovation can be regarded as architectural innovation. The probe-and-learn development reduces the risk of failing customer needs and effort by focusing on few product configurations for specific target groups. Probe-and-learn products are produced in small or medium sized series. A much wider range of product variants is defined at the beginning of development, but only a restricted range is initially developed in detail and taken to the market. The development and market launch of a base configuration helps the company to achieve strong customer interaction. This procedure enables the company to use in depth experience before detailing the whole product range. To achieve reasonable development lead times simultaneous engineering is usually the chosen lead time concept. In addition to effort reduction, experience with the initial pioneer products rise the success rate of the whole product development.

The project type **"release-oriented development"** is characterized by structuring the development process of complex products with the help of release units [11]. Release units have an interrelated product development and market launch depending on the design model lifecycle. The innovation degree for a release-oriented development can be described as a modular innovation. Release-oriented products need a high degree of modularity in their product structure. Therefore the changes on single components are easy to accomplish and have no effect on the functionality of the complete system [11]. Direct customer participation during the development process is rather unusual because release-oriented development focuses on a specific target group [13]. The type of production is small series to series production. Release-oriented products focus on a wide share of the market because the input for the development of release units is relatively high and expensive. The further development of products as well as the market launch of new variants is preferentially build in the context of release cycles. Major possible variants of a product are defined in the initial phase of a release-oriented development. The consolidation of release units takes place on predefined release cycles [11]. The development of product components which is eventually consolidated in a new release is usually performed in simultaneous engineering teams. Release-engineering reduces the degree of complexity in the product development process and uses synergy effects. The modularization of the product enables a continuous adjustment as well as an elimination of product variants within the context of release-oriented development [11]. The pioneer product concept enables the release-oriented development to further reduce development lead time between two product generations.

The project type **"add-on development"** is characterized by an incremental degree of innovation. The product is changed step by step and the used product technologies are existent [20]. The complexity of the development process is quite low as interdependencies are in general well understood. The add-on development is undertaken mainly independent from direct customer interaction but with a clear picture of customer needs in mind (generic development). Very short time to market and a large-scale production in the backhand are usually regarded necessary for the add-on development to achieve market success. The new product part is integrated into existing products to achieve maximum synergy effects. The product range must have a high degree of modularity and a high number of similarities to use this approach. The company checks the market resonance in a short time and with a low range of variance. The development risk is reduced and the company gains a time advantage from the pioneer product approach.

3.1 Capabilities Supporting Resource and Information Flows within an Integrated Collaborative Framework

The major capabilities considered in order to facilitate the pioneer product concept are cross functional teams, customer orientation, cost orientation, partner collaboration and process orientation.

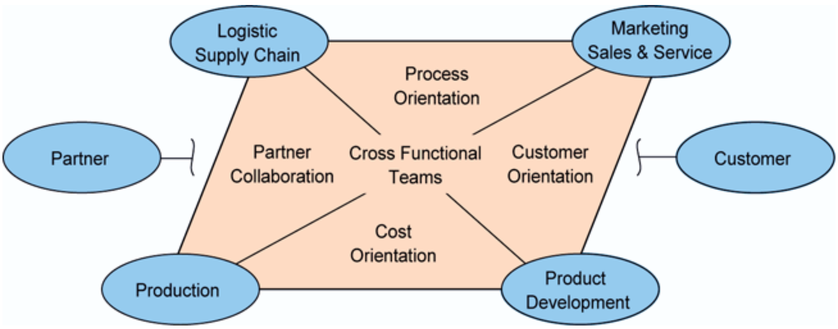

Fig. 4: Integrated collaborative framework with major capabilities

Cross-functional teams have a special characteristic that they are composed of people with different functions from different levels within and sometimes outside the organization. The motivation for companies to use cross-functional teams is usually to increase speed of projects, to master complexity and to intensify learning and creativity [18]. Many companies have established cross-functional teams but are only partly satisfied with the outcome. The leader of a cross-functional team usually has less authority than functional leaders but has to create a motivating environment integrating different functions and backgrounds. In order to succeed, key-stakeholders affected by the teamwork have to be taken into account. On the other hand, teams lose much of their effectiveness and efficiency if they get too big. Management support and sufficient capacity for the cross-functional team is often mentioned as an important success factor [15, 18]. The pioneer product concept means a clear focus on differentiating product features and reuse of approved concepts and hence reduces the complexity of the cross-functional team's challenges and development lead times. At the same time due to the rapid knowledge exchange between the stakeholders a reliable project can be expected.

Consequent customer orientation towards the perceivable customer benefit is an important condition for innovation success. The products are supposed to include differentiating features in contrast to competing products, solve problems or save money for the customer and possess a high relative quality [2]. Effective communication and dissemination of market intelligence are important to build an internal customer orientation eventually leading to products with a strong customer benefit. A very strong focus of the pioneer product concept on perceived customer value reduces the risk of failure in the market and ensures to meet the demanded quality.

Cost orientation quite often means abandonment of "nice to have" features in order to prevent over-engineering [21]. Focusing on the required functions and variants helps to keep product complexity at a manageable level. Realizing simplified designs with well defined interfaces ensures modular architectures and commonalities on component, module, product and platform level [22]. Consequent standardization and establishment of workflows to ensure the use of standards is an important lever to reduce product costs [21]. Cost reduction due to the application of the pioneer product concept can be expected due to the consequent reuse of existing and approved components. Resource and information flows are focused on the necessary flows in order to reduce cost of communication and unnecessary work.

Partner collaboration is a challenge with increasing complexity. Companies usually classify their potential partners in order to reduce complexity between partnership, mature and parental status [26]. The partnership status allows the partner to start development within a wide solution space. A mature partner fulfils the wishes by realizing components within sets of requirements and a parental partner implements design decisions. In terms of the pioneer product concept favoring approved partnerships helps to reduce lead times and risks of failure.

Process orientation is motivated from the lean philosophy [28]. It starts with the end i.e. the customer value in mind and clearly focuses on the value stream trying to avoid wasted resources and efforts. The flow concept and the pull concept are supposed to minimize intermediate stocks and waste and encourage the involved employees to constantly optimize the process [29]. The lean philosophy has been successfully applied to indirect processes like product development as well [21, 26] and it is suitable to facilitate the pioneer product concept and its objectives.

The pioneer products are developed as projects focusing on reduced lead times and the differentiating product features. In general, product creation process logic focuses on key milestones and the necessary documentation. However, the duration of the process phases depends on the individual project and the project management. Therefore it is generally possible to perform pioneer product projects within the established process logic. A difference might be that flexibility is generally regarded more important for pioneer products and the subsequent go/ no-go decisions can be formalized in greater detail within the key milestone logic.

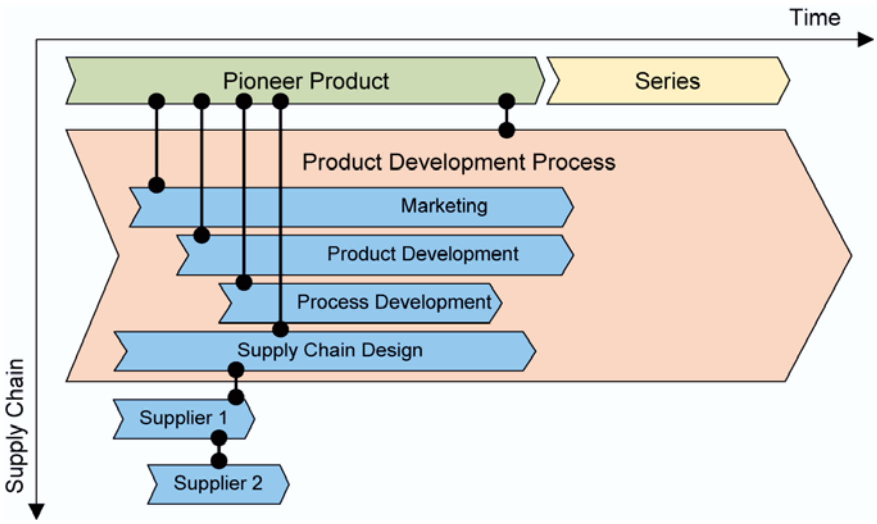

Fig. 5: Product development process

4 Discussion and Further Research

Pioneer product development has several potential advantages. Due to strict focus on the differentiating and customer relevant product features and consequent reuse of approved product components and partner networks the pioneer product concept can significantly reduce internal complexity with the potential advantages discussed in detail above. In addition, systematic scalable product development i.e. series migration after an initial pioneer product development is facilitated by a strong focus on cross-functional collaboration.

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A New Concept for Collaborative Product & Process Design within a Human-oriented Collaborative Manufacturing Environment

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Abstract
The paper discusses the introduction of an innovative human-oriented Collaborative Manufacturing Environment (CME) into the next generation of digital manufacturing. Following an overview of the current state-of-the-art, the conceptual background of the overall CME has been given. The CME will provide support for data analysis, visualisation, advanced inter-action and presence, ergonomic analysis, and collaborative decision-making. The paper also focuses on the module supporting of the collaborative product and process design. The innovative aspect, being the seam-less integration of virtual reality and decision making principles is also analyzed. The module will help "define" the proper solutions to the design or re-conceptualization problems, based on collaborative interactions and testing, which can occur in virtual environments.

Keywords
Collaborative Manufacturing Environment, Prototype Designer, Virtual Reality, Decision Making

1 Introduction

This increasing trend of globally distributed manufacturing relies heavily upon the swift and effective collaboration among dispersed people, groups and teams, the agility in enterprise, and the acceleration of customization in world markets, together with competitive ideas and products. Collaborative Working Environments (CWE) are outlined for the ways they can help these challenges to be met, through better modes of collaboration among all facets of a network.

Virtual Reality has reached an adequate level of maturity, as far as its use in design and manufacturing applications is concerned. Relevant demonstrators and systems addressing a number of related aspects [3, 4, 5, 11] have been suggested. Focusing on the collaboration aspect of engineering activities, several platforms for collaborative product and process design evaluation have also been presented in the scientific literature. The Distributed Collaborative Design Evaluation (DiCoDEv) platform enables the real-time collaboration of multiple dispersed users, from the early stages of the conceptual design, for the real time validation of a product or process, based on navigation, immersion and interaction capabilities [13]. In order to support collaborative work on shape modelling, a Detailed Virtual De-sign System (DVDS) has been developed, providing the user with a multi-modal, multi-sensory Virtual Environment [1]. An asynchronous collaborative system, called Immersive Discussion Tool (IDT), which emphasizes on the elaboration and transformations of a problem space and underlines the role that unstructured verbal communication and graphic communication can play in design processes [6], has also been presented. Another system for dynamic data sharing in collaborative design has been developed, ensuring that experts may use it as a common space to define and share design entities [12]. Various collaborative design activities are facilitated by a web-enabled PDM system, which has been developed and also provides 3D visualization capabilities [16].

Moreover, an Internet-based virtual reality collaborative environment, called Virtual-based Collaborative Environment (VRCE) developed with the use of Vnet, Java and VRML, demonstrates the feasibility of collaborative design for small to medium size companies that focus on a narrow range of low cost products [9]. A web-based platform for dispersed networked manufacturing has been proposed, enabling authorized users in geographically different locations to have access to the company's product data and carry out product design work simultaneously and collaboratively on any operating system [18]. The cPAD prototype system has been developed to enable designers visualize product assembly models and perform real time geometric modifications, based on polygonised representations of assembly models [15]. Another system, called IDVS (Interactive Design Visualization System), has been developed, based on VRML techniques, in order to help depict 3D models [10]. An agent-based collaborative e-Engineering environment for product design has been developed, based on the facilities provided by the AADE — a FIPA-compliant agent platform validated through a real-life industrial design case study [8]. Finally, addressing the needs for IT systems to support collaborative manufacturing, a new approach to collaborative assembly planning in a distributed environment has been developed [7]. Comprehensive reviews on systems, infrastructures and applications for collaborative design and manufacturing have also been presented in the scientific literature [14, 17].

Most of the web-based collaborative design systems either support fundamental aspects of collaborative design or are proof-of-the-concept demonstrators. Moreover, attribute oriented data, captured in simulation environments, must be capable of driving knowledge based decision making. Nevertheless, only limited capabilities exist for developing and evaluating alternative plans, based on competing process, alternate sources or different asset utilization options [2].

2 The Collaborative Manufacturing Environment Framework

In the context of the *DiFac* Specific Targeted Research Project, which is financially supported by the European Commission, an innovative VR-AR based Collaborative Manufacturing Environment (CME) for the next generation of digital manufacturing has been conceptualized. Its aim is to support real-time collaboration within a virtual environment for product design, prototyping, manufacturing and worker training. The CME is expected to provide the user with advanced capabilities, including visualization, group presence, interaction, information sharing, knowledge management and decision making.

The proposed CME will address the major activities in the digital factories, namely the product development, the factory design and evaluation, as well as the workforce training. Three pillars, namely Presence, Collaboration and Ergonomics, will underpin the methodological and technical realization. Since the future digital factory is a human-centred CME, it will be the human factors that will play the critical role of the foundation for the three above-referenced pillars. Six basic modules will be integrated into the proposed CME (three of them in the system level and another three in the application level) in order to support the respective activities (Fig. 1).

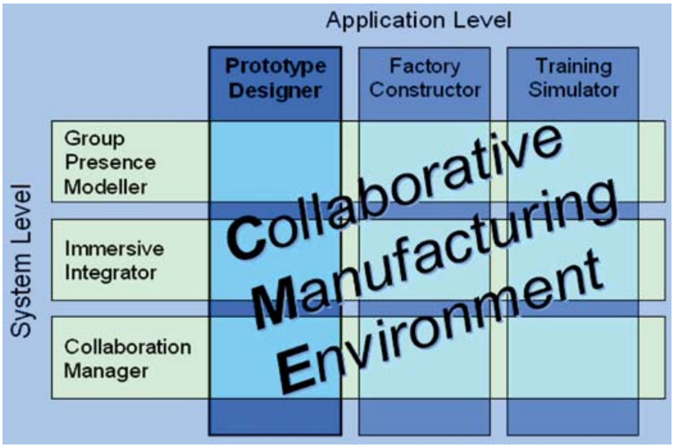

Fig. 1: The six basic modules of the CME and their interrelation

The system level consists of the *Group Presence Modeller* module, which aims at making groups of workers interact in a real collaborative working environment, dealing with the software aspect related to the visualization, perception and interaction, the *Immersive Integrator* module, which will enable all the work groups and group workers to collaborate with each other, aiming at realizing a hardware integration layer and a VR interaction metaphors toolset, for the developers of the application components, and the *Collaboration Manager* module, which aims at supporting both group decision-making and collaborative knowledge management.

The application level consists of the *Prototype Designer* module, which will provide the functionality for a web-based collaborative product and process design evaluation, the *Factory Constructor* module, which aims to provide the simulation of a complete virtual plant that will have the capability of completely emulating the real factory operations and the *Training Simulator* module, which will be used for training new workers and for retraining the experienced workers who will be working in a new or reconfigured group or with new facilities.

3 Collaborative Working Environment – Prototype Designer

Within this context, the *Prototype Designer*, being one of the basic modules of the innovative Collaborative Manufacturing Environment, will al-low the collaborative testing of ideas on virtual prototypes, by employing context-aware paradigms of immersive interaction. The use of intelligent quantified reasoning, will enable a multi-user assessment of alternative de-signs and plans. It will be further capable of suggesting to the designers, proper solutions to design or re-conceptualization problems, based on “testing”, which can happen in virtual environments. The concept of the *Prototype Designer* module and its links with the rest of the CME modules is graphically shown in Fig. 2.

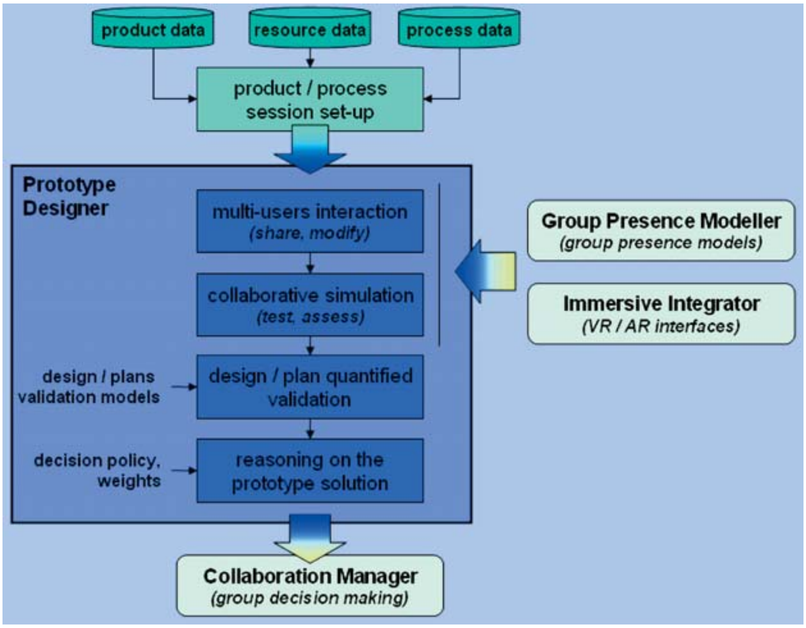

Fig. 2: The *Prototype Designer* module and its links with other CME modules

The *Prototype Designer* module will consist of the three components:

- the Rule-based Alternative Generation Mechanism,
- the Collaborative Virtual Testing Environment, and
- the Decision Engine.

3.1 Rule-based Alternative Generation Mechanism

Providing solutions for complex design problems requires a valid representation of data related to the resources used, the processes and the products. Data may be derived from information systems having already been installed in industrial sites (legacy systems). Available languages, such as STEP or XML, will be investigated in order to support the description of the product data.

Moreover, a basic *set of rules* will be specified and modelled so that it can be served as the handling means of the process data. The rules will be related to critical technical and legislative constraints, as well as to company and industrial standard practices, etc., which typically exclude a priori a number of values for a process parameter.

Both the rules and models of products and the processes and resources will be the *input parameters* to the *Rule-based Alternative Generation Mechanism*. The mechanism will be capable of producing a number of alternative rough design solutions, based on the data organization available and on the set of rules. In order for that to be achieved, a *process alternatives template* will be defined first, based on actual industrial standards and specific working practices. The template will include the basic process parameters involved in the definition of a design solution. With the use of the process alternative template, sets of values will be applied to the process parameters. This will be carried out automatically, or through user intervention for possible amendments of values or for alternatives elimination. The output of this mechanism will provide the candidate with design solutions to be verified, in terms of hands-on performance within the *Collaborative Virtual Testing Environment* (Fig. 3).

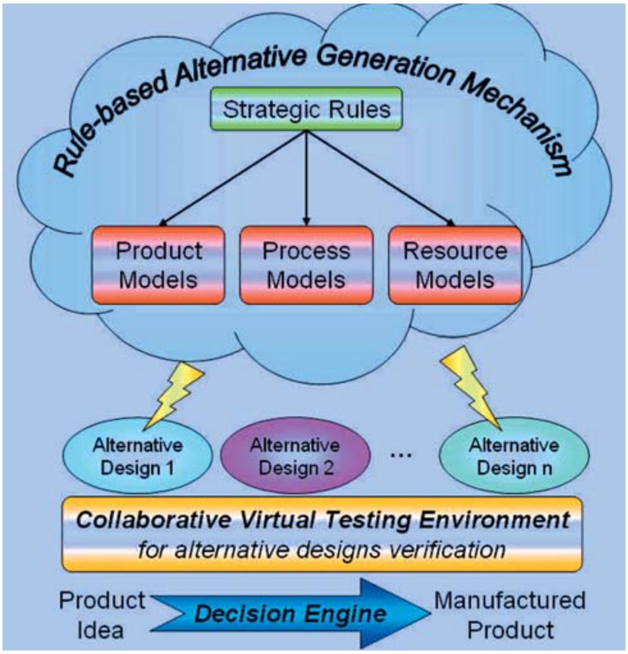

Fig. 3: Conceptual framework of the *Prototype Designer* module

3.2 Collaborative Virtual Testing Environment

The *Collaborative Virtual Testing Environment* will be a VR-based con-text-aware environment. It will provide the designer with the necessary functionality that would enable him to check, in an immersive and interactive way, the *feasibility* of each potential alternative design solution and to get *quantified* values for a number of performance indicators.

During the interactive virtual process performance, the user will be able to identify the non-valid solutions, namely those that involve problematic aspects, such as collisions between moving and static parts, ineffective use of tools due to space cons traints, poor accessibility for proper fitting, or ergonomically unacceptable situations (Fig. 4).

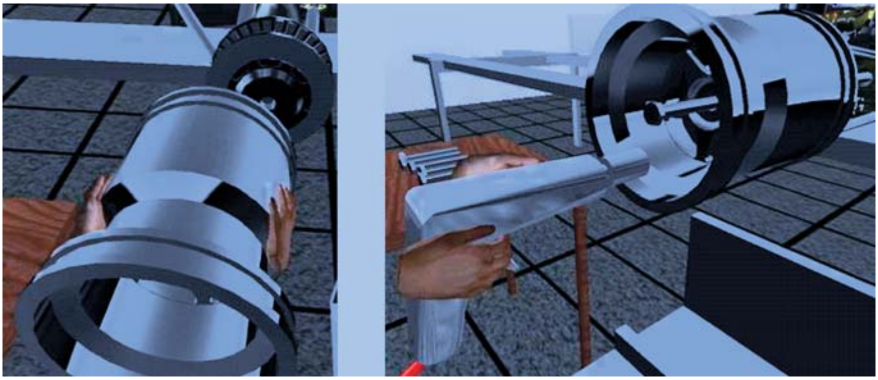

Fig. 4: Immersive & interactive virtual process performance

The user will be able to get quantified values for a number of performance indicators, with reference to the valid / feasible design solutions. More specifically, the user will be able to define a number of specific process performance indicators of interest, such as the cycle time, the process cost, the working volume, the mean fitting path length, the safety / damage measure, the ergonomic rating of the process, and eco-efficiency measure, and activate the respective recording tools for them. The valid / feasible design solutions, which result from the *process feasibility verification*, will be simulated in the *Collaborative Virtual Testing Environment*, either interactively or automatically. Quantified values for all the performance indicators, defined by the user, will be recorded for each valid / feasible alternative.

3.3 Decision Engine

This module will enable the user to define first the *decision policy* to be applied for the ranking of the design solutions. It will provide the user with the capability of *activating a list of criteria* and *setting weight values for each criterion*. The criteria represent the process metrics by which each alternative will be evaluated. For example, the user may wish to make decisions based on the assumption of higher relative importance for the cycle time, due to assembly line requirements, and for the working volume, due to special space restrictions. An appropriate assignment of weight factors could be as follows:

Tab. 1: Example of weight factors related to the Decision Engine

cycle time	process cost	working volume	mean fitting path length	safety / damage measure	ergonomic rating	eco-efficiency measure	TOTAL
0.30	0.1	0.30	0.05	0.05	0.1	0.1	1

A *normalization procedure* should be also typically specified to enable the homogenized consideration of all the performance indicators, in the context of the design alternatives grading. The appropriate normalization technique for both benefit and cost-type indicators will be defined. The procedure will be carried out in a transparent for the user way, based on the values of the performance indicators, recorded in the phase of the *quantified process validation*.

Using the normalized values of the performance indicators and the selected decision policy, the *Decision Engine* will calculate the utility of the different valid / feasible alternatives. The calculation framework will be specified upon common techniques of multiple criteria based decision-making. Customisations will be carried out to reflect the special characteristics of the specific working practices. As an output, the *Decision Engine* will provide the user with a relative ranking of design solutions. This output will be subsequently communicated to the *Collaboration Manager* to support further group decision making activities.

4 Implementation & Validation Considerations

The module of *Prototype Designer* will be based on a VR platform and will be appropriately enriched by features of the Group Presence Modeller and the Immersive Integrator and Collaboration Manager that will provide the basic functionality for sharing virtual environments. Robust interfaces among the components of the *Prototype Designer* will be defined, by utilizing standard data format languages, such as STEP or XML, for developing a seamless integration.

The usability and functionality of the *Prototype Designer* will be tested, in the context of the DiFac project, against real life industrial scenarios, on product and process designs, coming from sectors such as those of laser machinery and textiles.

5 Acknowledgment

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Towards a Framework for Managing Conceptual Knowledge in Distributed and Collaborative R&D Projects

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Abstract

Because of globalization and competitiveness, companies more and more often join their strength by gathering their R&D services into a virtual enterprise (VE) in order to develop engineering design projects in a more efficient way. The work we aim to present in this paper has been developed in the context of the European network of excellence Virtual Research Lab for a Knowledge Community in Production (VRL-KCiP). This network gathers 24 teams of expert researchers in the mechanical production field over 15 European countries. The works, which are carried out in the VRL-KCiP and in a VE are similar: engineering projects are lead in a collaborative and distributed way. The assignments of such virtual organizations (VO) are quite the same and consist mainly in producing collectively new knowledge in order to solve problems. Thus, managing knowledge is of major importance in such a context, due to the high value of knowledge today.That is the reason why, in this paper, we aim at presenting the framework of a system enabling conceptual knowledge management in virtual organizations.

Keywords

Networked research, research and development, collaborative engineering design, knowledge management, knowledge creation.

1 Introduction

Nowadays, worldwide economy and competition often lead companies to setup temporary alliances with other companies in order to respond to business opportunities. Those alliances, usually called virtual enterprises (VE), enable fast product or service development by making the best use of all the available resources. This kind of distributed structure can be found in other contexts such as research with virtual labs. The generalization of this concept of distributed structures leads us to a more general term, the virtual organizations (VO).

Those kinds of collaborative networks are emerging thanks to the development of new Internet-supported collaborative tools. Although there exist many forms of those organizations, they have common characteristics [2]:

- Networks composed of a variety of entities (organizations and people), which are autonomous, geographically distributed, and heterogeneous in terms of their operating environment, culture, social capital and goals.
- Participants collaborate to (better) achieve common or compatible goals.
- The interactions between participants are supported by computer networks.

The general term to refer to those distributed collaborative organizations is collaborative-networked organization (CNO). As we said previously, in CNOs, participants collaborate to achieve a common goal. This goal usually consists in solving a problem by improving knowledge in a particular area. Knowledge in such a context is highly valuable and has to be captured in order to be reused in future collaborations. Thus, one of the most relevant issues in CNOs is knowledge management (KM), that is to say how can we capture, capitalize, store and reuse it properly? In this paper we first aim to identify the main requirements concerning knowledge management in CNOs. Then we introduce a framework for supporting and managing conceptual knowledge[1] in this context. The methods and tools being developed within the framework are tested then used in engineering and research projects carried out by the network of excellence VRL-KCiP[2].

1 Conceptual knowledge refers to a person's representation of the major concepts in a system and the links between them.

2 VRL-KCiP: http://www.vrl-kcip.org

2 Requirements

It is usually considered that there are two kinds of knowledge: explicit and implicit knowledge [6]. Explicit knowledge is embedded into written documents (e.g. research publications, reports, etc.). Tacit knowledge is in people's mind and is acquired through experience; it is very hard, even impossible to make it be explicit. In CNOs context, we need to manage both of those aspects of knowledge.

In order to capitalize and manage explicit knowledge, we need to build a collection of documents. Yet, knowledge resulting from past work is embedded into written texts and schemas, which doesn't facilitate finding appropriate knowledge and reuse it: you need to read the whole document just to find a piece of information that interests you or sometimes nothing. So the documents content has to be modelized in another way in order to make knowledge easily findable and reusable.

The inclusion of tacit knowledge in a knowledge management system can be done through knowledge mapping [11] and users profiling [13]. A competences profile is associated to each member of the organization so that it is easy to find people owning the appropriate knowledge [9]. Indeed, finding appropriate partners for collaboration within a short time is of key importance for a CNO, especially in business context [1]. Yet, we have to keep in mind that competence profiling, in the context of a KMS, must be easy to build and to maintain. Actually, the system should require minimum effort and time from the user, otherwise it would neither be up to date nor used.

During the collaboration, experts have to work altogether and to combine they knowledge in order to create new knowledge. An interesting tool that can support this kind of task is conceptual maps (see figure 1). Concept maps are diagrams that represent organized knowledge [7]. Coffey and al [5] identify four main characteristics concerning concept maps: First, concept maps are composed of concepts and relationships between them. Concepts are defined as "a perceived regularity in events or objects, or a record of events or objects, designated by a label". They constitute the nodes of the graph, they are often represented by a labeled box or circle. Relationships, the arcs of the graph, are represented by connecting lines that link two concepts together. Those connecting lines include a label, word that specifies the relationship. A triple concept-link-concept is called a proposition, which is a meaningful statement (often called a semantic unit). The second characteristic of a concept map is that concepts are organized in a hierarchical way: the most general concepts are at the top of the diagram while more specific concepts are arranged below. The third point deals with cross-links. Cross-links are relationships between concepts of different regions or domains within the concept map. This point is very significant for knowledge creation because that kind of link often represents creative leaps for the knowledge producer. The last characteristic is the possibility to include examples or specific objects in order to make the meaning of a concept clearer.

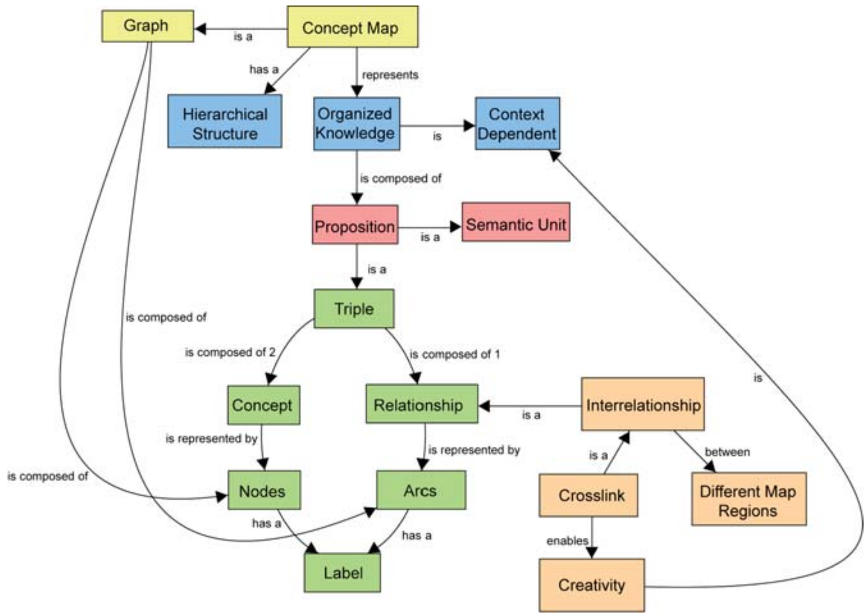

Fig. 1: A concept map about concept map[3]

In the field of knowledge management, concept mapping is considered as a useful vehicle for externalizing tacit knowledge (embedded in experts mind) and to allow this knowledge to be examined, reused and refined. Indeed it is a useful graphical support for sharing and discussing. Some tools based on concept mapping have already been developed in order to provide interactive capture, access and application of knowledge representing different experts perspectives [3].

In order to manage and integrate all those tools, we need a common knowledge base. The most efficient way of creating a knowledge base is to use ontologies [8]. Ontology is considered to be a powerful means to represent knowledge through the concepts of a specific area and the relations between them. Ontologies are generally represented by using a wide variety of logical languages, understandable both by human being and machines [10]

3 This concept map has been drawn with MotPlus, software edited by the LICEF research center: http://www.licef.teluq.uquebec.ca

such as propositional logic, first order logic and Semantic Web languages. In this paper we chose to focus on the languages stemming from the Semantic Web, the new standards developed by the W3C[4], considered as the future standards of the Internet. Actually, the ontological approaches for information exchanges on the Internet has to be considered in the next generation of KM systems [4], especially for CNOs since the WWW is the most easy and accessible way of exchanging information.

3 Framework for Supporting KM in CNOs

In this section, we aim at introducing a framework for a KMS, which could respond to the requirements presented above in the context of a CNO. The framework is shown in figure 2.

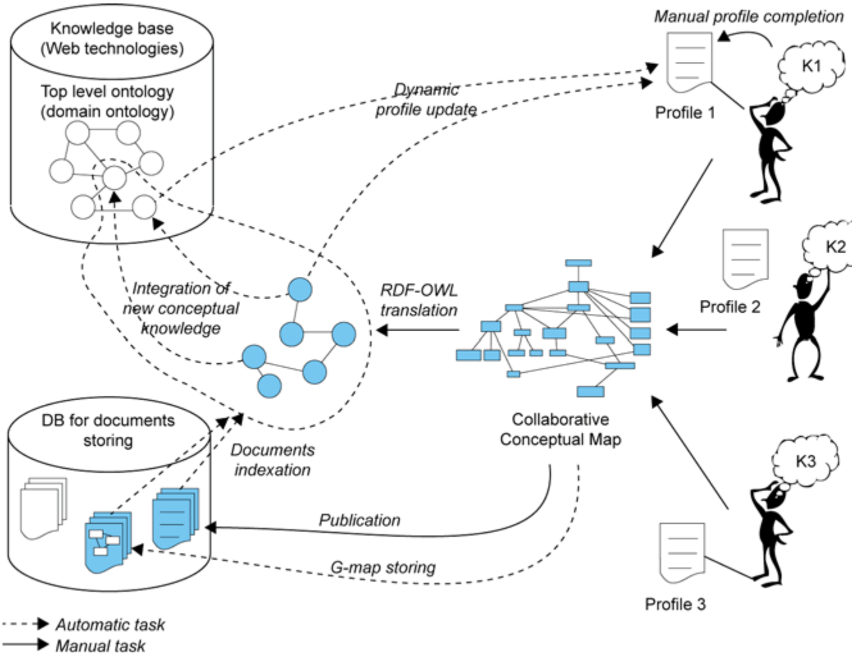

Fig. 2: Framework for capturing and managing conceptual knowledge in CNOs.

In this introduction of the framework, we only focus on how to capture knowledge and then how to update the knowledge base as well as the profiles. The other functionalities to include in order to respond to all the previ-

4 World Wide Web Consortium: http://www.w3.org

ous requirements would be tacit and explicit knowledge retrieval, that is to say finding appropriate people thanks to their profiles and finding appropriate knowledge in form of documents or concept maps.

Let us consider a collaboration between three experts. Each expert embeds his own knowledge. Each of them is characterized by a profile describing his knowledge and fields of expertise. Those experts have been hired for the collaborative project thanks to their profile. This profile has to be filled in manually as a first step and then it is automatically updated over the collaborations as we explain it further.

The experts then collaborate altogether by collecting and combining their knowledge. This task is supported by a concept map. This collaborative concept map helps experts to express, share and combine their tacit knowledge. Explicit knowledge can be linked to the concept map. For example, it would be possible to link a file (text file, image file, other concept map, web link, etc.) to a concept to explain it or to instantiate it. Actually, the experts build this concept map to link and organize the core concepts of their project.

When the concept map has been built, it constitutes a support to help the experts to write one or more documents (paper, report, deliverable, etc.) that clarify and make detailed knowledge resulting from the project be explicit. Indeed, detailed knowledge cannot be represented in concept map because the graph becomes rapidly unreadable and unusable. Nevertheless, a methodology based on concept maps and specific patterns (so-called bricks) has been developed in order to represent detailed scientific knowledge [12].

Once the project is over, the definitive concept map is stored in a document database and is also exported into RDF[5] and OWL[6] languages. Both of those languages stem from the Semantic Web. Thus, this new conceptual knowledge can be integrated into the knowledge base of the system, which is also based on Semantic Web technologies. Conceptual knowledge stemming from the project is linked to an upper domain ontology. The documents (the concept map and one or more publications) that have been created in the context of the project are indexed and linked to the knowledge base thanks to this new conceptual knowledge.

New conceptual knowledge is also used in order to update dynamically the profile of the project participants. So that, their profile is also indexed and linked to the knowledge base.

5 Resource Description Framework: http://www.w3.org/RDF/

6 Web Ontology Language: http://www.w3.org/TR/owl-features/

Thus, tacit and explicit knowledge can be retrieved by querying the knowledge base and can also be reused in future projects. It can be retrieved in the form of experts profile (in order to hire or question appropriate experts) for tacit knowledge and in the form of concept map or other documents type for explicit knowledge. One or more concept maps can be used as a basis for new collaboration projects.

4 Conclusion

The big issue, in collaborative networked-organizations, is to capitalize and manage knowledge produced over collaborations. Here “knowledge” means explicit knowledge as well as tacit knowledge. In order to achieve this goal, we introduced a framework based on several concepts. First, concept maps: they help to express, share, organize and capture tacit knowledge of expert people. Second, we use a knowledge base using Semantic Web technologies in order to integrate new knowledge and index and store all the documents related to this new knowledge. The last point is dynamic profiling: it enables to index tacit knowledge of expert people through competence-profiles and dynamically update those profiles depending on the contribution of experts over collaborations.

Therefore, we have a dynamic framework that is able to capture and capitalize explicit as well as tacit knowledge. From now, further work consists in detailing the use of the knowledge base and the best ways of reusing the capitalized knowledge. Based on the framework and the methods and tools being developed, engineering and research projects carried out by the network of excellence VRL-KCiP are now starting working this way.

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DEPNET: A Methodology for Identifying and Qualifying Dependencies Between Engineering Data

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Abstract
Collaborative design is a collection of the co-operated efforts undertaken by a team of designers. Due to multi-actors interaction, conflicts can emerge from disagreements between designers about proposed designs. Therefore, a critical element of collaborative design would be conflict resolution. In this paper, the DEPNET methodology is introduced to support conflict management. This methodology is based on a Unified Modelling Language (UML) traceability model to extract the data dependencies network. This will allow identifying the conflict resolution team as well as evaluating the impact of a selected solution. A case study within an industrial partner is described to illustrate this methodology.

Keywords
Conflict Management, Data Dependencies Network, Case Study.

1 Introduction

Due to multi-actors interaction in collaborative product design, conflicts can emerge from disagreements between designers about proposed designs [5]. Thus, a critical element of collaborative design would be the conflict management; which could be perceived as the succession of mainly five phases [9]: (1) Conflict detection, (2) Identification of the conflict resolution team, (3) Negotiation management, (4) Solution generation, and (5) Solution impact assessment.

In this paper, the main objective is to come up with methodological elements to allow the team identification and the assessment of the solution impact on product and process organisation. The identification of negotiation team constitutes a pre-requisite for conflict resolution. Indeed, conflict resolution cannot be achieved by one single actor; it requires the gathering of different expertise areas to avoid unnecessary iteration. In order to provide a solution to the detected conflict, design actors have to collaborate and negotiate forming this way the *negotiation team*. It is then important to identify the right actors to resolve a conflict, else new conflicts could occur.

Once a solution is generated, the latter leads often to modifications on a subset of the already defined product parts as well as on the process organisation. Indeed, the negotiation phase leads to a solution which often implies changing one or more input data of the activity where the conflict has emerged, and thus, generating a cascade of modifications on the already produced data. These modifications require a re-execution of a set of design activities necessary to achieve changes, and also an adjustment to the preliminary project organisation.

Therefore, negotiators identification and impact assessment are highly dependent on handled data during the design progress. This supposes knowing the dependency links between the conflict source data and the data previously produced. Consequently, solving these two phases mean:

- Identifying the dependencies network of the data handled during the design progress in order to define the negotiation team.
- Qualifying the data dependency links in order to assess the impact of the selected solution.

The remaining part of this paper is organised as follows. In section 2, the data dependencies network components are described. This network is composed of nodes and arcs representing respectively the handled data during the design process and the dependency links existing between them as well. Section 3 presents the DEPNET (product **D**ata d**EP**endencies **NET**work identification and qualification) methodology to identify this network. This methodology is based on a UML traceability model to track the design progress; allowing this way to extract the data dependencies network. Section 4 describes a case study to illustrate our approach. Finally, section 5 concludes with some perspectives.

2 Data Dependencies Network

2.1 Network Nodes: Handled Data

Design work returns with a succession of tasks to define a new product through the use and the generation of various product data. The handled data can be of several types: structural, functional and geometrical, etc. They correspond to the various descriptions of the product, elaborated by designers during the development process, in terms of geometrical entities, functions, bills of materials, CAD drawing, simulations, etc.

Depending on the margin left to the designer to elaborate data, on the values of data properties and on the context in which it is committed, product data can evolve through different states. Grebici et al. [3] identify four data states: draft, exhibit, enable and deliverable, according to the workspace where they are handled: private, proximity, project and public workspaces. These concepts are summarised in the following:

- Draft is a piece of data that one has to apply the modalities of creation and validation of hypothesis or solutions to a project or a design problem. They are defined by a design actor individually.
- Exhibit is a piece of data that one applies a persuasion modality in accordance with what is represented in either for convincing about the existence of a problem or for showing a solution and allowing a common construction and the point of view exchanged.
- Enabled traces are data the designer accepts to diffuse to others, after his agreement with a collective prescription to which he takes part. It is non-officially validated data but sufficiently convincing to be published.
- Deliverable are data that transmit a strong regulation. They have been formally verified and validated (by hierarchy). They are those contractual supports to being communicated to the customer.

2.2 Network Arcs: Dependency Links

According to Kusiak [7], a dependency between variables is the effect of change in a value of one variable on another variable. Whereas, for Wang [10], two components are said to have dependency relation if any of the two can not be completed without the other.

These definitions reveal that two kinds of dependencies may exist between two product data: *dependency at creation* and *dependency at modifi-*

cation. Both of these dependencies kinds will allow us to qualify a dependency link.

Dependency at Creation

Two data are said “dependent at creation” if the creation of one of them depends on the creation of the second one – this corresponds to the dependency definition in [10]. Some research works have attempted to define attributes to express this link, such as: the *relevance*, the *usage* and the *completeness* [2]. We are particularly interested in *the completeness* attributes which draw the actual data variation interval. The design actor should express how should be the variation interval of the consumed data. Higher is the completeness attribute value, smaller would be the input data interval variation. The completeness attribute is then considered as the “at creation dependency” measure. The completeness attribute values are:

0 Weak: the input data could be given below a certain maximum value
1 Not Vital: the input data should be given within a certain value range
2 Vital: the input data should be given with the smallest value range
3 Extremely Vital: the input data should be precisely given

Dependency at Change:

Two data are said “dependent at modification” if the change of one of them implies the modification of the second one – this corresponds to the dependency definition in [7]. Attributes such as *Level Number*, *Importance Ratings*, and *Probability of Repetition* [1] were proposed to define this dependency link. We focused on the probability of repetition attribute since it constitutes the hardest to obtain input for simulating an iterative development process. The *Probability of Repetition* reflects the probability of one element causing rework in another. Krishnan et al. [6] defines the dependency at change measure as the multiplication of both attributes: *Variability* and *Sensitivity*.

Variability is the likelihood that the output data provided by one task would change after being initially released. The variability measurement scale is:

0 Null: the output data don’t vary
1 Low: the output data varies but few
2 Moderate: the output data is instable
3 High: the output data is very instable

Sensitivity is the degree to which work is changed as the result of absorbing transferred product data. The sensitivity measurement scale is:

0. Null: output sensitivity is null to most input changes
1. Minor: output sensitivity is low to most input changes
2. Moderate: output sensitivity is medium to most input changes
3. Major: output sensitivity is high to most input changes.

Dependency Degree

In order to qualify the dependency link between two data, the dependency at creation and the dependency at change measures are aggregated to one criterion to express the *dependency degree* between two data. Therefore, the attributes completeness, variability and sensitivity are aggregated to measure the dependency degree (cf. Eq.1). As they are complementary attribute, a multiplicative utility function is utilised in the aggregation of the variability and sensitivity attributes (**V*S**). When the variability value is "0" and the completeness value is different from "0", the dependency degree value must be different of "0", since that a not null completeness implies a dependency at creation.

$$\textit{Dependency Degree} = \textit{Completeness} * (1 + (\textit{Variability} * \textit{Sensitivity})) \qquad (1)$$

Accordingly, the resultant range value of the dependency degree is an integer between 0 and 30, whereas {0, 1, 2, 3 and 4} denotes a weak dependency and a low risk of rework, and {15, 20, 21 and 30} denotes a very high dependency and a high risk of rework. The values {5, 6, 7, and 8} and {9, 10, 12 and 14} describe respectively a moderate and a high dependency and risk of rework.

3 DEPNET to Build up the Data Dependencies Network

The objective of the DEPNET methodology is to come up with methodological elements that allow the identification of data dependencies and then their qualification. In order to do so, the first step is to trace the design process progress by storing it in a database system. Then, a set of queries are applied on the obtained data to extract the network.

3.1 Traceability Model

Traceability in product development is defined by Hamilton and Beeby [4] as the ability to discover the design history of every feature of a product. Traceability dimensions can be described by answering the basic questions adopted from the Zachman framework [11]:

What are the traceable items: refers to the design objects, requirements, design decisions, etc. which will allow building up the data dependencies network. As design process deals mainly with consuming, exchanging, communicating and producing product data, the traceable items to represent by the data dependencies network are the handled product data.

Where the traceable items are: refers to the design actions handling the product data during the design process. Two management levels of the design process exist, the prescribed one and the emerging one. At the prescribed level, the process is composed of phases which are composed of planned activities. The emergent level corresponds to the non planned activities occurring during the design progress.

Who are the resources playing different roles in the creation, modification and exchange of the product data.

Why – How product data are created, modified and/or evolved the way it is; this corresponds to the design rationale behind the design actions.

When are the product data being created, modified and/or evolved; this corresponds to the starting and finishing date of the design actions (phase, planned activities and/or non planned activities).

To allow tracking the design progress in a database system, the various constructs discussed above are formalized in the UML model Fig. 1.

3.2 From Traceability Model to Data Dependencies Network

Based on the model presented in Fig. 1, a traceability tool was defined. This tool is a kind of an *a posteriori* workflow tool which allows declaring the design ongoing. This tool allows each actor involved in the design process to declare, when achieving his design action: the phase, planned activity or non planned activity he is executing; the objective if his design action; the input and the output data used and generated with the associated sensitivity, variability and completeness measures, as well as the maturity attributes (for enabled or deliverable maturities); and, the justification of the choices made during the design action.

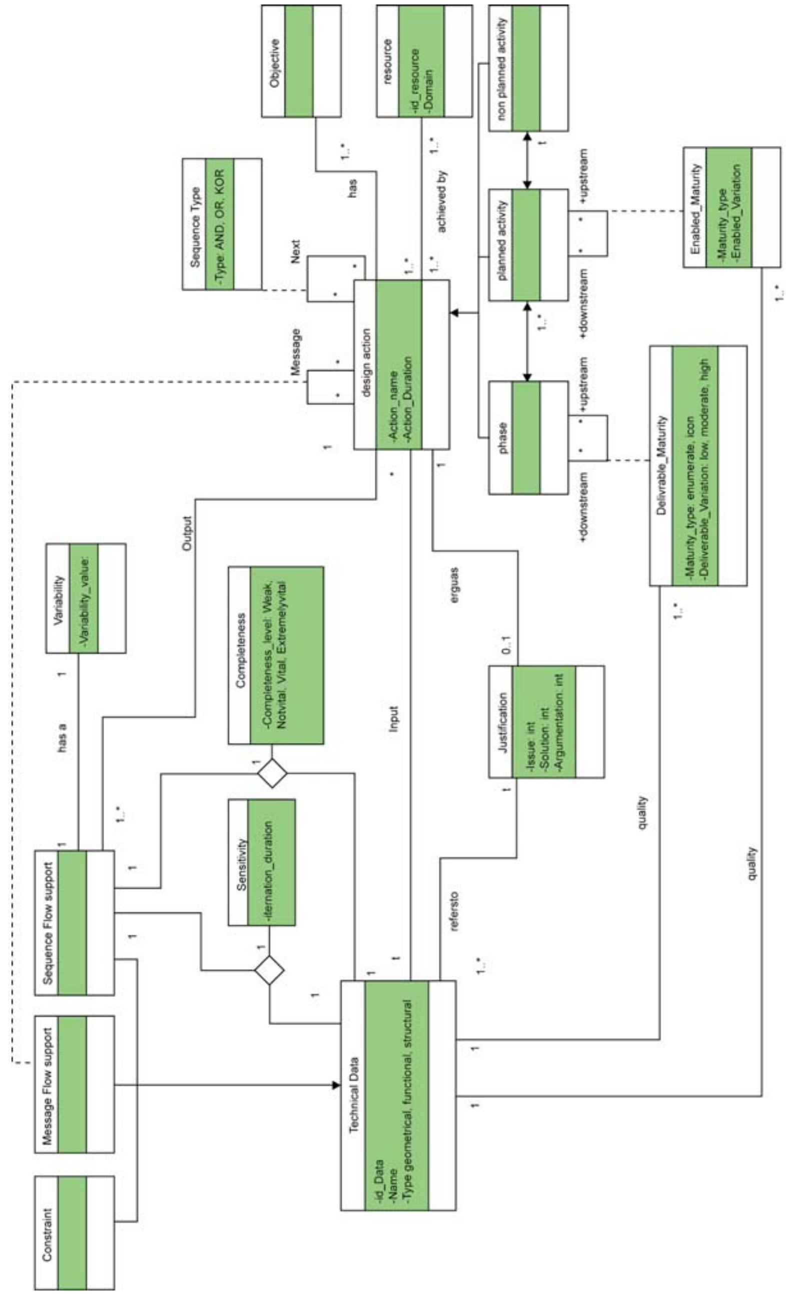

Fig. 1: UML traceability model to track data dependencies during design progress

These declarations must be done by all the involved actors during each one of their design actions. Once the design process ongoing is declared, the captured constructs are stored in a database whose tables correspond to the various classes of the traceability model described above. Indeed, each process element declared by actors corresponds to an instantiation of one of the database tables. Then, a set of queries can be applied to the stored data in order to collect the dependencies of the conflict source data. These queries are applied as many times as it is necessary in order to identify the whole conflict dependant data. Once the dependency network is extracted, it is possible to identify the negotiation team and the design activities to be re-executed. The data on which depends the piece of data source of conflict are identified through the network backward coverage; the piece of data source of conflict is the starting point. Then, a set of queries are applied in order to identify the actors responsible of theses data realisation. The formers (i.e. these actors) will then be part of the negotiation team that will resolve the conflict. We should note that the negotiation team could be dynamic during the conflict resolution process. Indeed, as the conflict resolution process goes on, new problems/conflicts may be detected. It is then necessary to invite the most qualified actors to solve these. As a result, the dependencies network could be used several times in the conflict resolution and the negotiation team composition could vary over time. Once a solution to the conflict is selected, the impacted data are identified through the data dependency network (i.e. a forward cover of the network starting from the data to which leads the selected solution).

4 Case Study: Turbocharger Design Process

The case study described in this section concerns the design process of a turbocharger within our industrial partner. The mechanical concept of a turbocharger is based on three main parts. A *Turbine Wheel* which is driven by the exhaust gas from a pump to spin the second main part, an *Impeller* – i.e. a Compressor Wheel – whose function is to force more air into the pump's intake, or air supply. The third basic part is a *Center Hub Rotating Assembly* (CHRA) which contains bearing, oil circuit, cooling, and a shaft that directly connects the turbine and impeller. At the beginning of the turbocharger design process, the concerned actors have at their disposal a set of specification as well as of requirements to respect.

According to these specifications, the impeller designer – i.e. compressor wheel process design responsible – starts his planned activity "to define the impeller part”. The latter has to define the impeller attributes composed of wheel cast-material, expected compressor inlet/outlet temperature etc. Once these attributes completed, the impeller designer define the exducer and inducer diameters of the compressor wheel as well as the 3D CAD drawing. The last task of the impeller designer is to define the impeller housing and how should this part be connected to the engine. In order to do it, the impeller designer calculates the impeller attributes Trim and A/R[1]. These attributes make the designer able to finish the impeller 3D CAD drawing.

Based on customer data, turbocharger specifications and impeller defined attributes, the turbine designer – i.e. turbine wheel process design responsible – concurrently starts his planned activity “to define the turbine wheel”. The turbine designer defines first a set of turbine attributes to reach the turbocharger performance. These attributes are composed of the wheel, nozzle ring and insert ring material, the inlet/outlet turbine pressure. Once these attributes defined, the turbine designer starts defining the wheel dimensions as well as the 3D CAD drawing of the turbine wheel. The wheel dimensions consist of calculating the exducer and inducer diameters. Then, the designer finishes his part design by defining the turbine housing by calculating the turbine attributes Trim and A/R.

Concurrently to the impeller and turbine parts definition activities, the CHRA designers specify their parts; based on the impeller and turbine defined parts and the turbocharger specifications. The CHRA designers have to define the bearing system (frame size, diameter, etc.), oil circuit (filtration, seals, etc.), shaft, etc. In order to do so, the designers have to exchange preliminary information making possible the process progress. Not only must the components within the turbocharger itself be precisely coordinated, but the turbocharger and the engine it services must also be exactly matched. If they’re not, engine inefficiency and even damage can be the results. Thus, it’s important that the concerned actors collaborate closely by coordinating their activities as well as the data exchange. Indeed, the different parts are highly dependent and modifying one of them impacts the others. Figure 2 recapitulates the precedence dependencies between handled data – an arrow defines the direction of a dependency.

Suppose that the turbine designer detect a conflict when defining the turbine 3D CAD drawing. In order to resolve this conflict, the negotiation team is formed. The negotiation members are those they participated in the design process leading to the turbine 3D CAD drawing. Hence, the team members are: the turbine designer, the impeller designer, the innovation team, the customer, the project manager etc. Once this team resolves the conflict, the

[1] A/R is the inlet cross-sectional area divided by the radius from the turbo centerline to the centroid.

modification impact is propagated according to the data dependencies network. Starting from the data to be modified the impact is propagated on the whole data dependencies network.

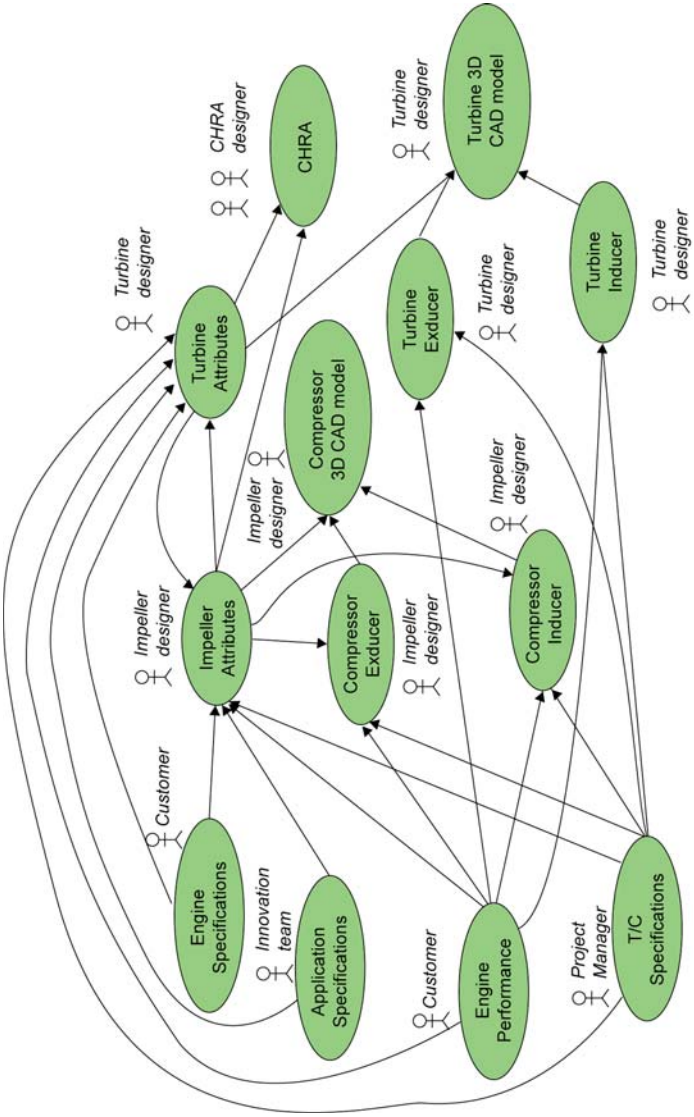

Fig. 2: Partial view of the data dependencies links during the turbocharger design.

5 Conclusions

In this paper, the DEPNET methodology has been introduced to support conflict management; in particular negotiation team formation and impact propagation on product data and process organisation. The proposed methodology is based on a process traceability method support to building up the data dependencies network composed of nodes i.e. product data and arcs i.e. dependency links. A tool is developed in order to implement this methodology and an illustration is done with a simplified case study [8].

However, further thoughts remain to be carried out for the process reorganisation problematic. In fact, the DEPNET methodology presents a support for conflict management. Based on data dependencies network, designers are able to identify negotiators and to propagate modifications on previously defined product data. These modifications often require a re-execution of activities producing data to be modified. In order to do so, it is necessary, first to identify the projects to reorganise, since a data can be used in several concurrent processes; and next, to define the needs to these processes and the objectives to achieve with them. The third phase would be to model and to analyse these processes. A description of the different aspects of the processes is then to be given. The execution and the coordination of the activities, the exchanged data and the allocated resources are to be analysed. Finally, based on the result of the modelling and the analysis phases, the process can be properly redesigned. Strategies to manage the overlapping of coupled product development activities are to be proposed to answer questions such as: when should downstream activity act on upstream data? How should the activities be overlapped when downstream activity cannot work on preliminary data?

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Distributed Product Development in the Framework of Modern Engineering Education

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Abstract
Competitive products and processes are developed by efficiently cooperating generalists and specialists. Integration of systems requires interdisciplinary teams. Beyond engineering expertise, project success highly depends on the ability to communicate and to document information. Globally integrated companies require staff that has both well-developed social and intercultural competencies. This is a challenge to modern engineering education. Universities can prepare engineering students for cooperative project work by moderating multinational teams and providing modern software and hardware tools to exchange information without restriction of time and place. Didactical and methodological approaches and suitable software and hardware tools are presented to contribute to efficient distributed product development.

Keywords
Distributed Product Development, Engineering Education

1 Introduction

Products and processes emerge by the cooperation of generalists and specialists in interdisciplinary teams. To be competitive, the engineering processes shall be carried out simultaneously to reduce the time to market and increase the quality of the development. Many companies, especially those who manufacture highly sophisticated products, have often nationally or continentally spread engineering departments, distribution centres and manufacturing facilities. Their component suppliers are commonly distributed all over the world and both sides strive for a close cooperation during the development phase.

For these reasons, globally integrated companies' success considerably depend on their technical know how and on the ability of their employees to cooperate using modern communication and information technologies. The staff requires social and intercultural competences necessary to communicate information efficiently and need to balance cooperation and competition to their cooperating partners.

The international master course Global Product Development (GPD) was established in order to meet these requirements in engineering education. This paper shows an overview of GPD, communication and collaboration tools which were used during the course and describes exemplary results.

2 The GPD Course

The master course GPD was established by the University of Michigan (UoM) in Ann Arbor, USA, Seoul National University (SNU), Korea, and Technical University Delft, Netherlands in 2000. Since 2002, TU Berlin is the European cooperation partner. The objective of GPD is an integrated systematic transfer of knowledge and methodologies regarding the whole product development process and the training of intercultural and social competencies as well as the improvement of management skills. Extensive project work, introduced and self-conducted case studies, as well as lectures support the achievement of these skills [1].

The central part of the course is the project work. At the beginning of the course, the students are assigned to multinational interdisciplinary teams. The task assigned to the students leaves a lot of space for creativity and self-realization. However, often conflicts of interest arise not only considering technical and economical difficulties, but also personal interests within the team. The design process is a process of negotiation [2]. The teams have to consider many phases of the product life cycle for their project work, fig. 1. They begin with a market and patent search to identify market potentials. The students focus on the customers and their environments taking into account that the product shall have several life cycles. A rough project plan has to be set up defining tasks, responsibilities, and milestones.

After the conceptual and embodiment design phase the students present their results, providing information among others about the differentiating factors to existing products or the product architecture that makes the product a global product. The design process has to be conducted in a systematic manner, i.e. the teams begin working on problem statement, requirement list, and function-structures via the selection of manufacturing processes, engineering calculations, and CAD drawing, and finalize their project by manufacturing the prototype.

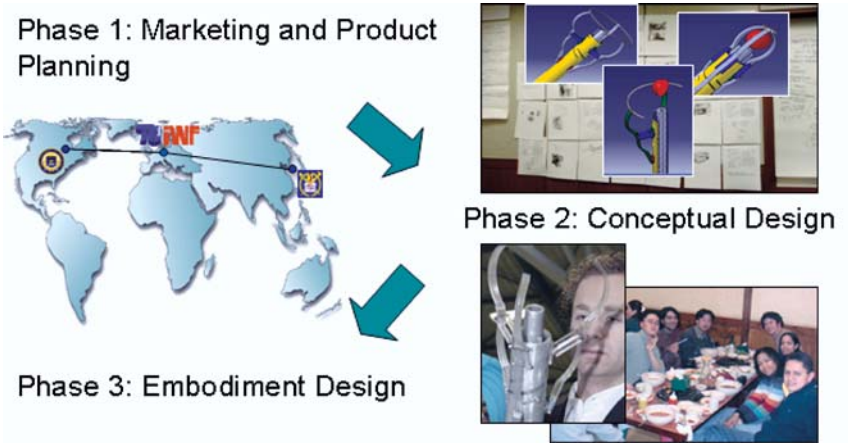

Fig. 1: Phases of the Project Work

With the exception of two face-to-face meetings, the overall development work is conducted by virtual meetings using different information and telecommunication tools. The first meeting is scheduled within the first month after the course begins and serves mainly team building purposes. After four months, at the end of the course, the second meeting takes place and the students assemble, test, and exhibit their prototypes at the hosting university.

During all phases of GPD lectures are given by the teaching staff and experts from industry and research depending on the topic. The case studies and exercises narrow down a topic in such a manner that the students can apply their learning directly to their project work [3].

3 Communication and Cooperation Tools for Product Development

Communication tools applied in GPD can be distinguished by the way of information flow. Synchronous communication tools allow fluent talks, while asynchronous tools do not. Typical synchronous tools are instant messaging tools such as MSN Messenger [4] or ICQ [5], software or hardware tools for audio (Voice over IP, VoIP) and video conferencing. In the first case, the tasks are executed by a personal computer (PC) and in the second case by a special stand-alone machine. Instant messengers allow people to conduct a dialog by typing and reading the contributions of other members. The typed content appears nearly in real-time. Audio over VoIP is available as pure software, which needs a PC, speakers and a microphone, e.g. TeamSpeak [6] which is an open-source software. VoIP can be transmitted by hardware such as VoIP telephones, which can be directly plugged to a digital subscriber line router (DSL-router). Instant messengers have been extended by the functions of audio and video conferencing. During video conferencing, content such as the image of the others participants, a sketch captured by a document camera or the video-out of a PC can be exchanged.

Often used asynchronous tools are email and shared workspaces. Shared workspaces are software applications running on standard PCs or servers with various functionalities. Normally, they can be used to upload and download documents, post information, and to organize groups. EGroupWare [7] is an example for such software. However, there are tools with special functionalities, e.g. Virtual Office [8], which synchronizes the changing of slides in presentation without sending the content of a slide.

The suitability of a tool depends mainly on the content to be exchanged, the group size, the infrastructure, i.e. the bandwidth of the internet access and the computing power of the PCs or video conferencing machines as well as the media and language competencies of the participants. If information has to be well structured and documented as well as if participants of a group are less practiced in dealing with the used language or not familiar with the topic, email is beneficial. The advantage of shared workspaces is that all team members are up to date concerning their project work, i.e. each team member has the same degree of information and is working with the newest information. The major advantage of audio and video conferencing is that also non-verbal information can be exchanged. By this, the chance of misunderstanding can be reduced. In specific cases, chatting is more convenient compared to audio and video conferencing, because the effort for setup the equipment is lower, i.e. no headset and webcam is required and text is always readable compared to speeches which might be difficult to understand due to technical difficulties or unfamiliar pronunciation. Furthermore, the text can be saved as a protocol of the whole discussion.

Besides tools supporting the group communication, there is a comprehensive amount of tools to ease the distributed group work. Tools are for example MindManager [9], which can be used for online-brainstorming, SMART Board [10], which brings along whiteboard functionality, and Microsoft Project [11] for server based project management. Many CAD software such as Unigraphics NX [12] or ProEngineer Wildfire [13] have a feature called product data management (PDM), thus people can work together on one product at the same time.

In contrast to specific software features of a program, such as PDM, which enables users to work together using solely this program, application sharing as a universal approach. By using application sharing software solutions almost all computer programs can be used distributed. The working principle of application sharing is to make a picture of the master desktop and send this picture to the participants. The content shown on the master desktop can be manipulated by all participants. In the viewpoint of users, the main difference between the software solutions is the possible amount of participants sharing an application and the usability. Software examples are NetMeeting [11], which allows few persons to share an application and Bridgit [10] which allows up to 500 participants to join. The disadvantage of application sharing is the required broad bandwidth of the internet access of all participants.

4 Communication and Cooperation Tools Used in GPD

The course GPD is used as a test bed to analyse and evaluate different didactical and methodological approaches. Therefore course constraints are slightly changed from year to year to determine the influence of different measures. The variables have been the provided information and communication tools and the degree of support for the student teams.

The scale and thus the importance of the communication are shown in figure 2. The effort for communication compared to the effort for project work by the students on their own is only between 20 to 30 percent lower, depending on the project phase.

In 2002, the complete project work was based completely on the initiative and self-organization of the students. The only support given by the teaching staff was a rough course schedule including the dates of the three mile stones. Under these conditions, it took a long time until the students contacted each other and started to work on the projekt. The main reasons for this were on the one hand the reservation of the students and on the other hand the missing group hierarchy respectively definition of responsibilities. At the beginning of the team forming stage, students used almost only email for communication and later on they addes MSN messenger and the communication platform called Teamboard [15]. The Teamboard is a shared workspace and was implemented by the Seoul National University. Each

GPD team got their own domain on this platform, where they were able to upload and download files as well as post information and questions on a virtual notepad.

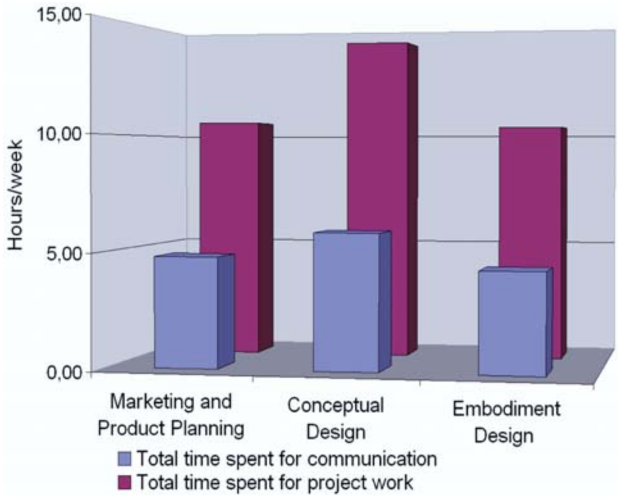

Fig. 2: Time spent for Communication and for Project Work

In 2003, the videoconferencing systems of the universities were available for the teams after four weeks from the course begin. Most of the teams decided to go on without using the video conferencing, since it didn't offer any added value for them in comparison to email and instant messaging tools. They especially criticized the strongly restricted availability of the universities' video conferencing systems. The use of PC-based audio and video conferencing software tools was not satisfying due to the low available bandwidth and the resulting low sound quality.

In the year 2004, the video conferencing system was available for the teams from the beginning of the course and was used frequently. At the first meetings, a member of the teaching staff joined the meetings and if required, moderated the meeting.

The use intensity of the Teamboard is considerably lower compared to email and instant messaging tools all over the years. The low utilization rate of the Teamboard can be explained by its similar functionality to emails concerning the requirements for the project work.

In 2005, a document camera was additionally available and in 2006 also a SMART Board.

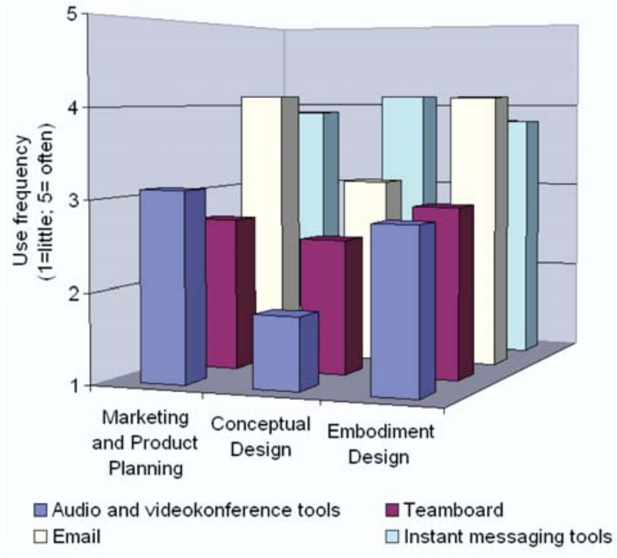

Fig. 3: Use Frequency of Communication Tools

Statistics show that students prefer different tools depending on the content and thus on the project phase, figure 3. At the beginning of the course, the students used MSN or ICQ to discuss product ideas, the targeted market, and the responsibilities within the team. Mainly email was chosen to update each other on the results of the market and patent research. Only a few groups used Skype [16] frequently. In the second phase when the students worked on the conceptual design, the use frequency of email increased slightly and the use frequency of instant messaging tools and audio or video conferencing tools decreased considerably. In the phase of the embodiment design, the need for coordination increased and the students used synchronous tools to arrange things in a fast way.

5 Results of the Project Work

The topic of the project work in the GPD course of 2003 was to make an existing product internet-ready, i.e. to modify a product in such a manner that it is more attractive to the customer by providing advanced functionality, which makes use of the internet. One team selected the bicycle rental service of the German railway (DB) for their project work. The approach of the existing service is that the customer looks for a bicycle of DB distributed throughout the city.

By the modified approach of the students, the added value for the customer is that he can locate the nearest bicycle and reserve it using the internet or calling the rental company. Furthermore, the bicycle provider can guarantee the operability of his bicycles, because the conditions of most important components, e.g. the tires, are monitored. The status of the bicycles is sent via internet to the service department of the rental company. Figure 4 illustrates one approach worked out by a GPD group, which is based on fixed docking stations spread out all over the city. The availability of the bicycles is monitored by cameras.

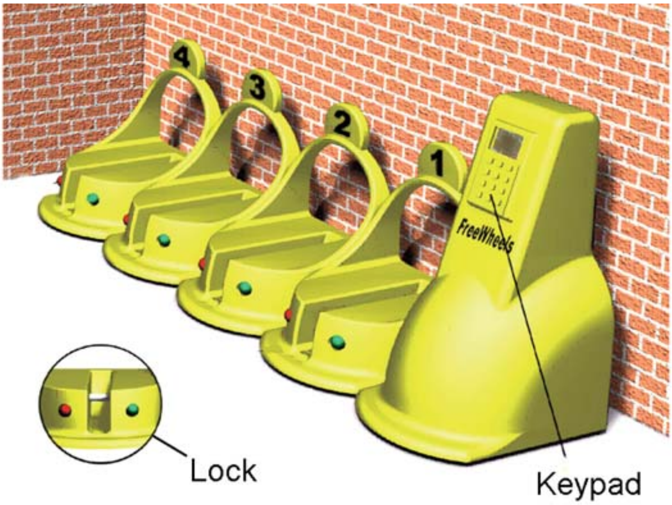

Fig. 4: Bicycle Rental System

The topic of 2004 was to develop a product marketable in two regions, one in a developed and one in a developing country. The main idea was to sensitize the students to identify new market opportunities by products which also consider people, which form the bottom of the wealth pyramid [17]. One team developed a fruit dryer, which is appropriate for Central as well as South America and Australia. The partly extreme humid weather and large farming populations of both regions make them ideal target areas.

The tasks of the teams of 2005 were to redesign existing products with emphasis on sustainability issues [18]. One idea was to reduce the need of resources for baby and child transportation. They developed a stroller, which can be transformed into a bicycle so that the transportation during babyhood and childhood could be fulfilled by one device, figure 5.

Fig. 5: Convertible Stroller

6 Summary, Outlook, and Acknowledgements

The globalisation of the markets gives many companies the chance to increase their marketing areas and to reduce the costs, e.g. by setting up or transferring plants to regions with lower costs of labour or by establishing co-operations with companies from other regions in the world. Furthermore, the time to market can be reduced by working 24 hours a day in teams living in different time zones. However, these potentials can be only exploited if the employees of globally acting companies are trained in teamwork, have outstanding competencies concerning social and intercultural aspects and are familiar with modern communication and collaboration tools.

The master course Global Product Development has been established to contribute to modern engineering education by considering the altering way of how engineers will work together in the close future. In GPD, students from three different continents develop global products using modern communication and collaboration tools and considering sustainability issues. However, the course is also used as a test bed to analyse and improve these tools as well as approaches for cooperation.

Education concepts like GPD can also be used in the field of further education. Employees from globally acting companies can improve their collaboration capabilities and learn how to use modern communication tools efficiently. The distant learning approach with face to face phases can offer companies good opportunities to qualify employees for challenges in global engineering. GPD can provide a realistic training for engineers to learn how the world of global business and cooperation can work. We gratefully acknowledge the funding by the Volkswagen Foundation.

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Romanian Research Network for Integrated Product and Process Engineering – INPRO

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Abstract
The paper presents relevant aspects for building the Romanian Research Network for Integrated Product and Process Engineering (INPRO). Based on the principles of integrated engineering and by building a collaborative virtual environment, 9 research centers and a national research institute have decided to share their competencies and knowledge in the field of integrated product and process engineering. The integration of each partner in the INPRO network and the work modality are shown in the Joint Program of Activities. The main actions that are described in the paper are the creation, consolidation and development of the network, initiation and development of jointly executed research activities and spreading of excellence. Finally, some conclusions are elaborated.

Keywords
Co-operative Platform, Integrated Product and Process Engineering, Knowledge Management, Virtual Design and Manufacturing

1 Introduction

Virtual organization is one of the potential and ideal places for knowledge management processes since knowledge is a 'culture' among teams or partners. Therefore, it becomes a suitable place to apply the knowledge management practice to support its functional and operational process. Increasing product complexity, shrinking design cycle times, and explosive global competition are forcing organizations around the world to collaborate in ways not previously considered. The virtual organization focuses around the idea of a group, which is not constrained by traditional boundaries of space and time. A strong virtual organization has to identify the strategic options for building the knowledge sharing culture in order to become competitive [2, 4, 6, 7].

This research represents the extension to the national level (in Romania) of the Virtual Research Laboratory for a Knowledge Community in Production (VRL-KCiP) Network of Excellence (NoE), project financed by the European Commission in the 6th Framework Program (FP6 2002-IST-NMP-1, Contract no. 507487) [10]. In the context of the national Excellence Research Program (CEEX) we have developed an integrated engineering network (started from 2006), INPRO [3] which allowed a clearer vision of the research orientations, a better quality of research results and the link with the European Research Area. The main research activities of the INPRO project are: development of new research tools and platforms for collaborative design and manufacturing, product models and product development processes, knowledge management.

2 The Context of the INPRO Project

Many product development projects require co-operative work between research team with various competences, which are geographical distributed. When such a project team is set up, all required knowledge must be considered to solve a certain conception problem in a collaborative environment. The product development process has changed dramatically in the last decade because of the progresses in the information and communication technology (ICT) field. Nowadays, the product development is a result of a collaborative design process in network [4].

The researches in the field of integrated product and process engineering are developed by research centers, laboratories from universities all over the world. In Europe 24 of them are partners in the VRL-KCiP NoE [6]. In Romania, the scientific research has a spread tendency, because of the low capacity of using and sustaining the research results by industry. The academic research has to be improved because of the result integration in the academic courses. So far, the main research-development-innovation (RDI) fields are correlated with those established by the European Commission for R&D. Therefore, there is an initiative for integrate the national scientific research in the European Research Area [1].

The INPRO network joint 136 members (83 PhD, 41 PhD. students, 8 researchers and 4 master students) from 9 research centers of the Universities of Timisoara, Bucharest, Iasi, Brasov, Bacau, Suceava, Sibiu and Oradea and a national research institute. They have decided to share their competencies and knowledge in the field of integrated product and process engineering. The project proposal is based on the idea of linking the Romanian scientific research to the European Research Area using the bridge created by the participation of the Politehnica University of Timisoara (UPT, through the Integrated Engineering Research Centre) in the European project VRL-KCiP. Through the INPRO project are developed RDI activities that include fundamental, applicative researches of pre-competitive level and are made in common by the network's partners. At the organizational level, the network is based on a long time partnership between the partners and the establishment of the following research poles: South Pole (Bucharest), East Pole (Iasi-Suceava-Bacau), Central Pole (Brasov-Sibiu), West Pole (Timisoara-Oradea), as it is shown in figure 1. The regional research centers will concentrate the scientific research and the human and material resources of high performance from their region.

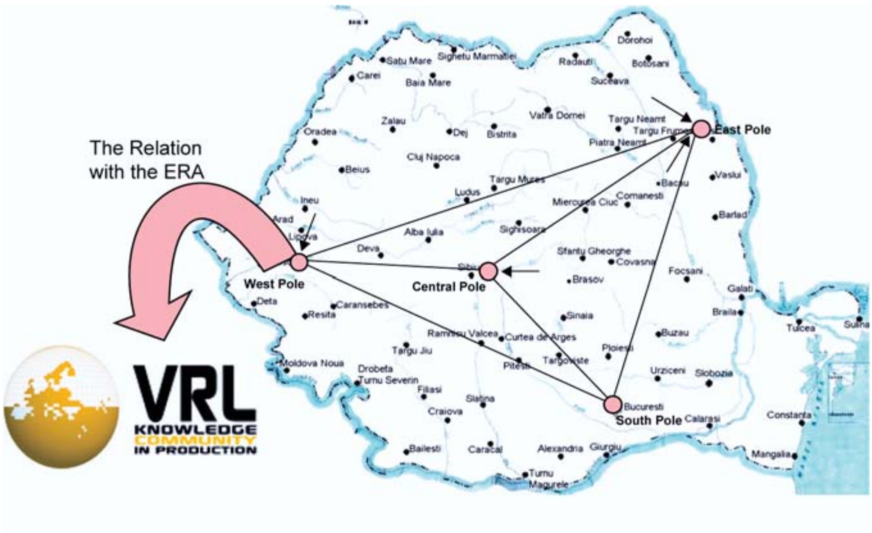

Fig. 1: Relations between the research poles inside the INPRO network and the link with the European Research Area

The specific strategic objectives followed by the creation of the INPRO network are: (1) setting up a manufacturing knowledge base in the field of product and processes integrated engineering, (2) increasing research activities performance, stimulating the specialized research team foundation in the priority R&D fields and facilitating the access to the EU research programs, (3) enhancing of the human resources education process by including the young PhD. students in the joint research activities and by assure the access to the disseminating activities in the INPRO network and the connection with VRL-KCiP NoE, (4) facilitating the mobilities inside the INPRO network and the VRL-KCiP NoE, (5) superior valorization of the existing material research base and research cost reduction by creating the possibility to common use of the partners' extant infrastructure, (6) managerial skills development in the scientific research field and increasing the capacity for new financial resources identification.

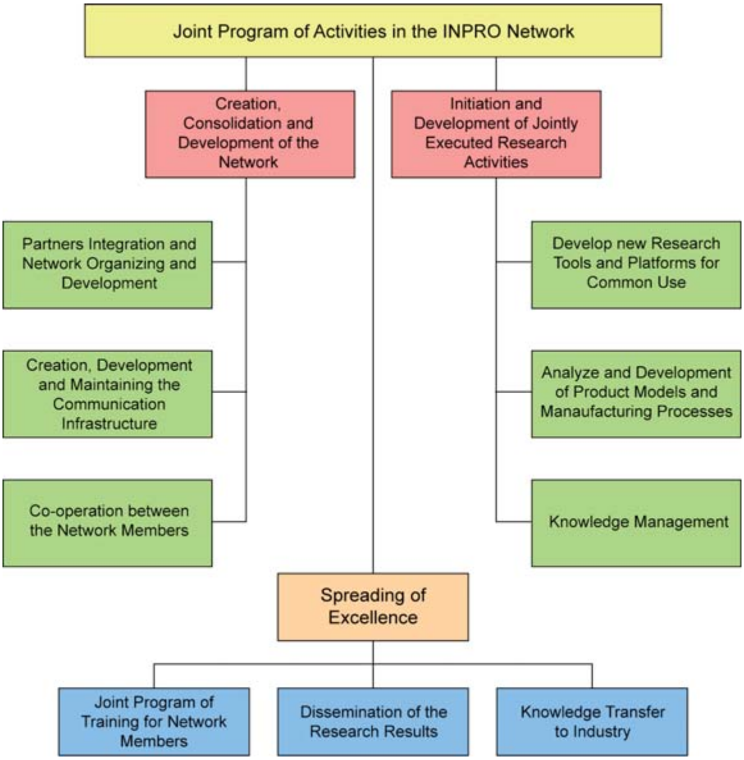

Fig. 2: The INPRO network's Joint Program of Activities

The operational objectives are: (1) creation, consolidation and development of the INPRO network, (2) initiation and development of jointly executed research activities, (3) spreading of excellence. The specific strategic objectives are realized by the Joint Program of Activities depicted in fig. 2. It consists of managerial aspects for organizing the INPRO network, but also the methods and tools that are used for the virtual collaborative environment development.

3 INPRO Network Creation, Consolidation and Development

3.1 Partners' Integration, Network's Organizing and Development

These are focus on adapting the organizational activities of the network through a strategic plan, for identifying the most demanding industrial requirements, defining the knowledge map and a competence profile regarding the current expertise of each member. In addition, there will be developed a policy to strengthen relations between the research activities. The work phases are:

Definition of a strategic plan for the partners' integration – there will be formulated the strategic priorities of the network by using the SWOT method for the diagnosis of the internal and external environment. Each year the strategy will be up-date.

Developing and maintaining a continuous living and upgraded vision on future industrial needs – a marketing research by opinion poll method will be developed for the industrial needs identification regarding research, development and innovation. Each partner will distribute and collect the questionnaires in his geographical area each year for the vision up-date.

Define a knowledge map and a competence profile is necessary to determine the current expertise of each member, by collecting the individual competencies in INPRO network. The preliminary ontology and the knowledge map will be built. These will be actualized each year.

Development of a policy to strengthen the relations between the research activities – The methods and tools that will be applied are in the field of researchers' motivation and implication.

3.2 Creation, Development and Maintaining the Network's Communication Infrastructure

This will focus on defining, developing and managing common tools for internal and external communication and knowledge sharing. The work phases are:

Definition of tools for internal communication will facilitate the collaborative work in the virtual environment. The tools that will be used are visioconference (VC) equipment (will allowed the connection with the VRL-KCiP NoE, by using the experience of Timisoara team), servers and specific software for the knowledge management and sharing common knowledge databases.

Definition of tools for external communication will support the activities for the spreading of excellence from the network to the external environment. The network's web page includes links to the partners, activities developed, results, news and e-journal.

Demonstration of software tools and, where is possible, making them available to other partners through the Internet – The software own by the partners will be available to all INPRO network members through Internet and they will support the common research.

3.3 Co-operation between the Network Members

With the aim to sustained the collaboration between partners, but also with other national and international Networks, there will be formed an *Adviser Council*. This will focus on encouraging mobility of the partners, their common work for articles and books and coordinating the PhD topics (joint supervision of PhD students). The work consists of:

- *Encouragement of mobility* – Exchange of personnel and cooperation on diploma student projects and master projects are important integration aspect that has a great interest for all the network members.
- *Co-ordination of PhD topics, initiation of joint supervision of PhD students* – To facilitate the exchange of PhD students a database of subjects and candidates for PhD research is created. This will support joint supervision of students' projects and the PhD thesis presentation in the network frame.

4 Initiation and Development of Jointly Executed Research Activities

4.1 Develop New Research Tools and Platforms for Common Use

This activity is the base for future collaborations and synergies by integrating the partners in the network. The work phases are:

- *To develop a common knowledge base to support collaborative RDI activities within the network* – The methods and tools that will be focused on the inventory of the actual resources of the partners and a database creation, which will be available to all partners on Internet.

- *To provide knowledge management and engineering tools* – We shall buy and install specialized software tools as: MindManager, TextMining.
- *To contribute to different content aspects of the common toolbox* – process knowledge for early design evaluation, cost modeling frameworks and re-use knowledge and other. There will be created software applications for knowledge management and integrated design.

4.2 Analyze and Development of Product Models and Manufacturing Processes

These two basic concepts will be the support for knowledge modeling. The modeling final step will concern the complete life-cycle processes of product and the corresponding knowledge, in order to allow a fast performance evaluation of the product during the design process [8, 9]. In addition, this work will focus on a large and complete state-of-the-art survey in many technological fields of production, processes, strategies and practices, with respect to both scientific and industrial reference. The work phases are:

- *The definition of a product life cycle model with integration of external service partners* – The goal is to made a critical analyze of the existing models (double cube, multi-view, integrated product etc.) and in an original manner, by integration and extensions, we will obtain a new model.
- *Development of life cycle controlling models to analyze the economic, environmental and social impacts* – Methods and tools to analyze the material and energy consumption, the generated losses, the needs of maintenance, repair, re-cycling and re-use in economics terms will be developed. These methods will be held for the economical life-cycle impact evaluation and they will be tested and validated by the industrial partners.
- *To take into consideration rapid prototyping processes such as Reverse Engineering (RE), Rapid Prototyping (RP) for tele-engineering and rapid manufacturing* – The goal is to study and investigate the existing RE and RP methods and processes used by the partners and develop new applications.

4.3 Knowledge Management

This is an activity developed based on the ICT techniques in order to constitute a very innovative network for future dissemination, both in Romania and at a European level. Knowledge management related to production fields will have to be implemented in a distributed web-based platform accessible to the network partners. The work phases are:

- *To collect and formalize knowledge about production processes by defining the actual limits (related to cost), publishing examples of use, good practices etc.* – The knowledge collection will be done by communication methodologies, using questionnaires, and the formalization. In the same manner there will be developed the c*ollection and formalization of knowledge about virtual design and manufacturing* and the process of *providing knowledge in process simulation, remote analysis, simulation and visualization of process parameters*.
- *Definition of knowledge management methodologies and tools for sharing knowledge and applications for demonstration inside the Network,* such as: ontology based systems, tools for knowledge management in production, including data mining and machine learning techniques. For knowledge capitalizing, using and disposal, web tools will be used.
- *Development of new working methods based on new methods for knowledge and communication management* – We will elaborate new work methods regarding the ICT tools and Internet platform. New methods for process optimization will be developed that will allow the interoperability of the application for the product development.

5 Spreading of Excellence

5.1 Joint Program of Training for Network Members

Advanced training and educational procedures, which will address students, researchers and key staff of the network's members will be developed using the VC system. The work phases are:

- *Creation of a cycle of distributed conferences* using the VC technique – Minimum 3 VC section per partner each year, alternatively hosted by each Pole centers of the network will be organized. Each year there will be made a CD (distributed in the network) with all the VC presentations.
- *Harmonization of curricula in the specific domains of manufacturing engineering,* through the review of the curricula in order generalized the experience gained by each partner.

5.2 Dissemination of the Research Results

This task will be held into national and international scientific community. The participation to international conferences in VRL-KCiP NoE will be encourages. The work consists of:

- *To support the interaction between the national network and international networks and programs* – The network members will have access at the organized VC in the VRL-KCiP NoE.
- *Organization of seminars or international conferences with academic or industrial destination* – INPRO network partners will co-organize each year an international conference.
- *Dissemination of the results in prestigious scientific organizations* – The INPRO members will be ambassadors in national and international scientific organizations.

5.3 Knowledge Transfer to Industry

During this activity the knowledge transfer to the industrial community will be encouraged. The work consists of:

- *Creation of a roadmap for technology transfer* – The local Chambers of Commerce and Industry will sustain the knowledge transfer to industry in each partner's area. Industrial workshops will be organized where specific INPRO's research results will be presented.
- *Creation of a common inheritance and installation of the tools for the evaluation of the potential openings to industry* – On the INPRO network web site there will be created a database consists of the practical results and the research themes that were solve for industry by each partner. This database will be up-date each year.
- *Definition of a policy for the intellectual protection and the defense of the rights of ownership* – We shall create a guide for the intellectual property rights protection.

6 Conclusion

Setting up of the national research network in the field of Integrated Product and Process Engineering (INPRO) attend the strategic objectives in high RDI. Also, it derive from the need of reducing the research fragmentation in the field, for building of a common resource (material and human) base that assure the possibility for complex researches in modeling and simulation of product and processes associated with their life cycle. It will be create a dynamic structure and a collaborative platform in integrated design that will allows its members to participate in cooperative design projects with industrial applications.

The share information process needs the information change into knowledge. Their variety is from the determination of the product specification to the end of lifecycle, including the processes and the manufacturing systems design [4]. The integration inside the network will be the base for the communication system development between the partners and for the establishment of a knowledge community.

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Facing Multi-Domain Complexity in Product Development

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Abstract
Controlling product complexity turned into an important issue for product development. This paper introduces a methodology for analysis, interpretation, and optimization of complex systems comprising of interdependencies between several domains. Therefore, the multi-domain matrix is introduced as an extension of known matrix approaches. Furthermore, analysis criteria for system structures are defined that base on graph theory.

Keywords
Product complexity, multi-domain matrix, DSM, graph theory

1 Introduction

Complexity in product development continuously increases, yet it has not been satisfactorily addressed in the literature and practice. Product complexity is e.g. driven by the market demanding individualized and multifunctional products [1, 9] and turned into an important issue for product development. Adaptations affect all aspects of product creation and require methods of complexity management.

Most approaches for controlling product complexity focus on its reduction [2]. Although it is purposeful to avoid unnecessary complexity, it is not favourable to reduce it at any cost, as complexity often relates to customer relevant attributes. A further positive aspect of controlled product complexity is its use as a barrier to product plagiarism [10]. Benefits of controlled complexity are invisible to product imitators and e.g. allow for efficient adaptations without showing this knowledge in the product itself.

A multitude of system features are only defined by its structure rather than by its implied components [8], e.g. the system robustness. A major requirement for the creation of robust systems is to identify significant structural characteristics and to derive suitable optimization. An effective method for controlling complexity allows for the prediction of change impact [4] extending to different domains, e.g. departments and people in charge [6]. This paper introduces a methodology for analysis, interpretation, and optimization of complex systems comprising of several domains.

2 Methodology

The methodology consists of three steps: system definition, multi-domain-analysis with derivation of relevant subsets, and analysis of selected network constellations. The system definition covers the collection of available input data and desired output data as well as the linking between both. During multi-domain analysis output data are generated, which are applied in the third step to detailed analysis and interpretation. Results serve for better system understanding and as initial point for specific system optimization. For representing network information specific visualization forms, design structure matrices (DSM) [3] and strength-based graphs, are used. As DSM typically focus on dependencies between elements of one domain, the approach is extended to interactions between multiple domains.

3 System Definition

The first task in system definition is to identify relevant domains [7] on the right level of detail. Then interdependency types between domains must be determined. E.g., "components" can be linked to "functions" by the meaning "realizes". It is recommended to arrange the domains in a square matrix (Figure 1) with the meaning of domain linking written in the matrix cells. This matrix is named multi-domain matrix (MDM).

At first, one must define the meaning that can be extracted from existing data (e.g., databases or interviews). Criteria for the selection are data availability as well as reliability. As shown in Figure 1, two matrices that link between the same domains are differing in inverted link order. The second meaning corresponds to the first one as its passive counterpart.

After specifying available data input, target domains have to be selected that serve for analysis and interpretation. In addition, it must be specified how these target domains must be determined by available networks, because one intra-domain network (connecting elements in-between the same domain) can be determined by different data input (see the next chapter).

	Components	People	Data	Processes	Milestones
Components	Component impacts component	Person works on component	Component represented by data		Component completed at milestone
People			Person generates data		
Data	Data required for component	Data required by person		Data required for process	Data available at milestone
Processes		Person works on process	Process generates data	Process information transfer	Process completed at milestone
Milestones					

Fig. 1: Multi-domain matrix with exemplary link meaning

4 Multi-domain Analysis

The multi-domain analysis helps identifying intra-domain networks, which provide useful information because of structural characteristics (e.g. feedback loops). Four possibilities exist for computing an intra-domain network from dependencies between two different domains (matrices connecting different domains are named inter-domain matrices): E.g., dependencies between people can be derived by linking of people to documents. This represents a typical scenario in product development, because designers dependent on other designers due to data transfer. Of course, the network of people can be acquired without regarding a second domain. However, it is often easier to take a detour for the following reason: people would have to be asked to whom they are connected because of document transfer in order to acquire dependencies between them; obviously, this question would be hard to answer. However, if documents are introduced as a second domain, people must only declare which documents they provide and which ones they require. Dependencies between people can then be automatically derived from acquired information.

- Case 1: An intra-domain network is derived from one inter-domain matrix; Figure 2 shows the logic dependencies as well as the matrix alignment in the context of the chosen example. I.e., dependencies between people can be derived from people's linking to documents: two people are linked (without direction), because they work on or access the same document.

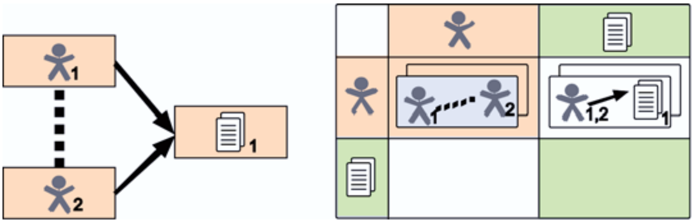

Fig. 2: Computing an intra-domain network by one inter-domain network

- Case 2: An intra-domain network is derived from one inter-domain and one intra-domain matrix (see Figure 3); person 1 and person 2 work on separate documents; however, document 1 is required as input for working on document 2, which causes the dependency from person 1 to person 2.

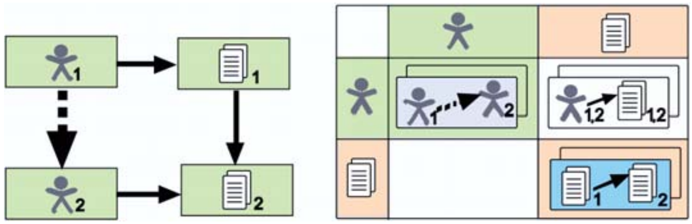

Fig. 3: Computing an intra-domain network by one inter-domain and one intra-domain network

- Case 3: An intra-domain network is derived from two inter-domain matrices. Figure 4 shows: a dependency directed from person 1 to person 2 is computed, because person 1 works on document 1 required by person 2.

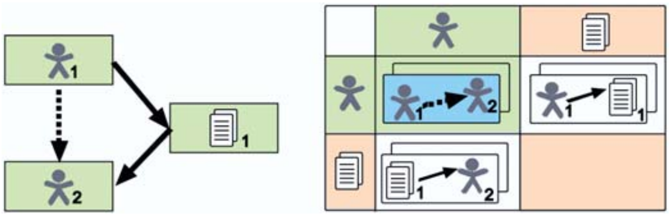

Fig. 4: Computing an intra-domain network by two inter-domain networks

- Case 4: An intra-domain network is derived by two inter-domain and one intra-domain matrix; Figure 5 shows: a dependency is directed from person 1 to person 2, because person 1 works on document 1 required for the compilation of document 2; finally, document 2 is required by person 2.

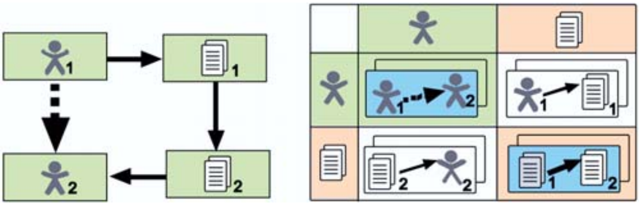

Fig. 5: Computing an intra-domain network by one intra-domain and two inter-domain networks

If several domains are available, computational possibilities allow for the creation of numerous intra-domain networks. These have to be evaluated regarding their suitability for further analysis and interpretation. If e.g. the majority of resulting network elements is mutually linked without any distinctive structural differences, such a network does mostly not inherit significance and will not provide helpful information. As well, the quality of ascertainable information is of major importance, as significance of computed networks directly depends on this input information. Some networks will be derivable from existing systems (e.g. PDM-systems, process plans, bill of materials etc.). In this case, the effort of information acquisition is lower and quality of input data is higher than by interviews.

5 Analysis of Selected Intra-domain Networks

Analysis criteria are available (Table 1) that base on graph theory and allow for consideration of intra-domain networks. The example in the table refers to a network of components linked by change impact. Interpretations are rather case specific and depend e.g. on the origin of considered data. Thus, transfer of interpretations between different use cases is problematic. Furthermore, the criteria must be considered in their combination of appearance. It is rather impossible to provide rules of thumb and the belief in significance of isolated values can be misleading. Software support is imperatively required and must permit flexible use of analyses. Most criteria are already applied in methods of product development, e.g. activity and criticality represent element characteristics in influence portfolios [5].

Tab. 1: Analysis criteria for intra-domain networks (Part 1)

Analysis criterion	Explication	Example
Active sum	Quantity of outgoing relations	Components of highest impact
Activity	Division of active sum by passive sum	Degree of active participation
Articulation node	Only node connecting two sub graphs	Change impact must pass by node
Biconnected component	Sub graph only connected by articulation node or bridge edge	Canceling one relation prevents probable change impact
Bridge edge	Only edge connecting two sub graphs	Change impact must pass by edge
Criticality	Multiplication of active sum and passive sum	Degree of network integration
Distance	Specifies the distances between nodes in a structure	High values represent indirect impact to/from node
End node	Node possessing only incoming (passive) relations	Component only receives change impact
Feedback loop	Circular sub graph	Change impact finally affects the originating node
Hierarchy	Node branching out in different levels	Spreading change impact based on specific element
Isolation	Nodes without any relation to other pars of a structure	Component is not affected by any change impact
Locality	Surrounding nodes of a central node because of existing edges	Nodes connected by outgoing edges receive direct change impact
Passive sum	Quantity of incoming relations	Components receive most change impact

Tab. 1: Analysis criteria for intra-domain networks (Part 2)

Analysis criterion	Explication	Example
Proximity	Specifies the distance from other nodes in the graph	Node with high proximity receives/provides direct impact
Reachability	Node can be reached from other nodes by dependency paths	Node with high reachability receives/provides impact from many nodes
Shortest path	Shortest connection between two nodes by edges	Most probable change impact propagation
Spanning tree	Sub graph connecting all system nodes	Required relations for reaching all system elements
Start node	Node possessing only outgoing (active) relations	Component only spreads change impact
Strongly connected part	All nodes can mutually be reached by a specific path	Each node can possess change impact to any other node in the sub graph
Traingularization/ Sequencing	Sequential or block order of nodes	Best adaptation sequence for change propagation

6 Case Study

The case study observes the student group “TUfast” located at the Technical University of Munich. The team develops a race car compliant to the Formula Student regulations. The design process is highly distributed, involving 35 engineering students. Typical problems such as purposeful modularization and optimized distribution of information are apparent. The TUfast-group relies on very fast development processes, because a new race car is set up annually. Furthermore, repeated fluctuation of team members raises difficulties for the group. Structural information was collected in order to identify critical constellations and provide suggestions for optimization.

Five domains were identified for the layout of the scenario: components, people, data, process steps, and milestones; all dependencies were acquired by interviews. The dependency meaning can be seen in Figure 2. Based on this, five intra-domain networks were analyzed in detail. Two of them concern the organizational structure of team members and are presented in the following.

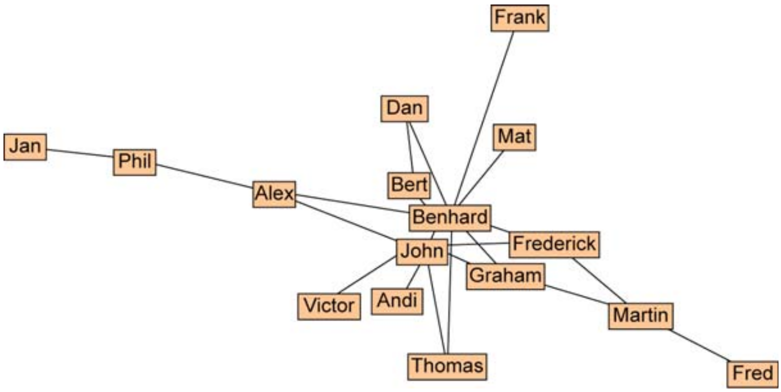

Fig. 6: Sub graph of people linking based on people's linking to components

The inter-domain network of people linking has been derived from a component and a data related point of view: the first resulting interdependency meaning is: two people are linked, because they work at different components that possess a mutual change impact. Different weights of dependencies between two persons result, if people are linked by more than one component change impact. Figure 6 illustrates a subset of the resulting network in a strength-based graph and focuses only on bidirectional dependencies. The positioning of elements in the graph result from the repulsive force between elements and the attraction force of interdependencies. People located close to each other work on several components that are linked by change impact. The closeness of people in the graph can be interpreted as importance of cooperation. Nine complete clusters exist in the entire people network comprised of three people each. In all clusters, Bernhard and John are involved. Furthermore, a large quantity of feedback loops exists in the structure, wherein Dan, Bernhard, and John are most included. Furthermore, 15 hierarchies can be identified, comprehending between 14 and 18 people on 3 hierarchy levels. As so far all members take part in the weekly team meeting, the subset of bidirectional linking in Figure 6 suggests reconsidering people's coordination. Many team members require bidirectional coordination that cannot be efficiently executed in the overall meeting (time consumption for other team members). Furthermore, three people form the core of the team possessing enormous coordination demand. Bidirectional exchange should be prioritized based on the quantity of component change impact. Obviously, people who require intense coordination must dispose of adequate communication support.

A further people network has been computed by two complementary inter-domain networks, which connect people and data (Figure 7). The interdependency meaning is "person generates data" and "data required by person". The resulting dependency meaning is: "an edge points from one person to another, if the first one generates data the second one requires". Although it seems rather complicated, the structure is highly significant: two different groups of people can be identified; the first group located in the middle of the graph possesses intensive active and passive interactions. Those people require large amounts of data and provide data as well. The second group is characterized by strictly passive dependencies. These people only require data for their design tasks. However, work results are not fed into data descriptions any more. Possible optimization measures concerning the design process are: people that generate data should be supported in data propagation, e.g. by visualizing people's direct surrounding of their data receivers. This facilitates the push principle of information flow.

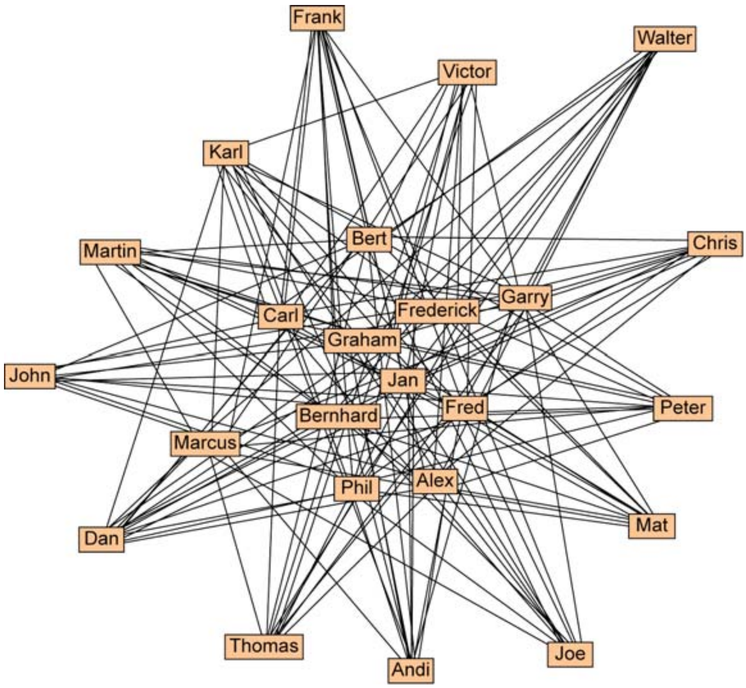

Fig. 7: Dependencies between people based on people's linking to data

Additionally, people depending on data provision should know about their suppliers. Visual support of individual supply chains permits a pull principle, for example in case of supply delay. Furthermore, planning of people fluctuation in the team gets possible: If a person, belonging to the passive data receivers, quits the team, the team management has to find another person executing the tasks; however, the information flow is not disturbed, because other people do not depend on information provision of the team member in question. If a team member from the inner group of the graph representation will change, it must be guaranteed that a new team member knows about his obligation of data provision. If such a new team member is not introduced correctly, major disturbances of the design process may result.

7 Conclusion

The presented approach provides methodical support for analysis, interpretation, and optimization of complex design processes regarding the variety of involved domains. The use of multi-domain matrices allows for improved data acquisition, because complex dependency logics can be split up into easier ones. Furthermore, the approach provides possibilities of systematized deduction of intra-domain networks, which are suitable for analysis as well as intuitive user comprehension.

When applying the multi-domain approach availability of input data must be clarified. Extraction of information from data bases is less time consuming and promises higher data quality than acquisition by interviews. However, interviews may offer highly interesting insight, as this input information has never been prepared systematically before (undocumented experience knowledge).

The multi-domain matrix allows for the integration of several development aspects simultaneously. Relevant networks can be derived automatically with low expenses. However, some facts seem to be problematic: so far, no rules are available to reliably conclude from analysis criteria to detailed network meaning. For this reason, comprehensive experience in system modelling and analysis is required. If people trust in the significance of single analysis results, misinterpretation may occur. For this reason, future research must focus on providing target-oriented rules for application of analysis criteria and their interpretation.

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Using Evolutionary Algorithms to Support the Design of Self-optimizing Mechatronic Systems

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1 Introduction

Nowadays, most mechanical engineering products already rely on the close interaction of mechanics, electronics, control engineering and software engineering which is aptly expressed by the term mechatronics. The ambition of mechatronics is to optimize the behavior of a technical system. Sensors collect information about the environment and the system itself. The system utilizes this information to derive optimal reactions. Future mechanical engineering systems will consist of configurations of system elements with inherent partial intelligence. The behavior of the overall system is characterized by the communication and cooperation between these intelligent system elements. From the point of view of information technology we consider these distributed systems to be cooperative agents. This opens up fascinating possibilities for designing tomorrow's mechanical engineering products. The term self-optimization characterizes this perspective [1].

Although there are numerous examples for the use and benefit of mechatronics (e.g. VDI Guideline 2206), the potential benefits of self-optimization as a feature of mechanical engineering systems are only now beginning to be recognized. It is clear that we need imagination to define machines that possess inherent partial intelligence. An additional challenge is the particular characteristic of self-optimizing systems, namely that in the design stage we can no longer anticipate all the system's possible constellations and behaviors because self-optimizing systems also exhibit cognitive abilities and are able to learn. [2]

An essential milestone of the development of a self-optimizing system is the principle solution as a result of the early design phase “conceptual design”. The principle solution determines the physical and logical mode of action of the components as well as the type and arrangement of the components, without defining these in detail.

A new and powerful paradigm such as self-optimization naturally calls for new development procedures [2]. In recent time, a standard-methodology has been developed, which enables developers to create and specify a principle solution for a self-optimizing system [2, 3, 4]. In addition to this, new approaches for the development of technical systems have been made: On approach is, to use evolutionary algorithms (EA) for the design and the optimization of technical systems. An analysis of the current state-of-the-art has shown two application classes [5]: On the one hand with evolutionary algorithms the shape of components is sketched or optimized (e.g. in [6, 7, 8]). On the other hand, evolutionary algorithms are used to optimize or design the behavior of a technical system (e.g. in [9, 10]). In this paper we will introduce a new approach to the design of principle solutions. We are using an evolutionary algorithm to generate and evaluate the principle solution.

The paper is structured as follows: The next chapter describes self-optimizing systems. The following shows the representation of the principle solution. The fourth chapter explains the evolutionary design process. At least chapter five validates the approach by an application example.

2 Self-optimizing Systems

The key aspects and the mode of operation of a self-optimizing system are illustrated in Figure 1. The self-optimizing system detects factors that influence the system. The factors may originate in its surroundings (environment, users, etc.) or from the system itself. The self-optimizing system determines its currently active objectives on the basis of the encountered influences. Objectives formulate the behavior of the system that is required, desired, or to be avoided [1].

The self-optimizing system is able to adapt the system of objectives autonomously. This means, for instance, that the relative weighting of the objectives is modified, new objectives are added or existing objectives are discarded and no longer pursued. Adapting the objectives in this way leads to adaptation of the system behaviour. That is achieved by adapting the parameters and where necessary the structure of the system. The term parameter adaptation means adapting a system parameter, for instance changing a control parameter. Structure adaptations affect the arrangement of the system elements and their relationships. Here we distinguish between reconfiguration, which changes the relationships between a fixed set of available elements, and compositional adaptation, in which new elements are integrated into the existing structure or existing elements are removed from it.

We express self-optimization as a series of three actions that are generally carried out repeatedly. This sequence of actions is designated a self-optimization process:

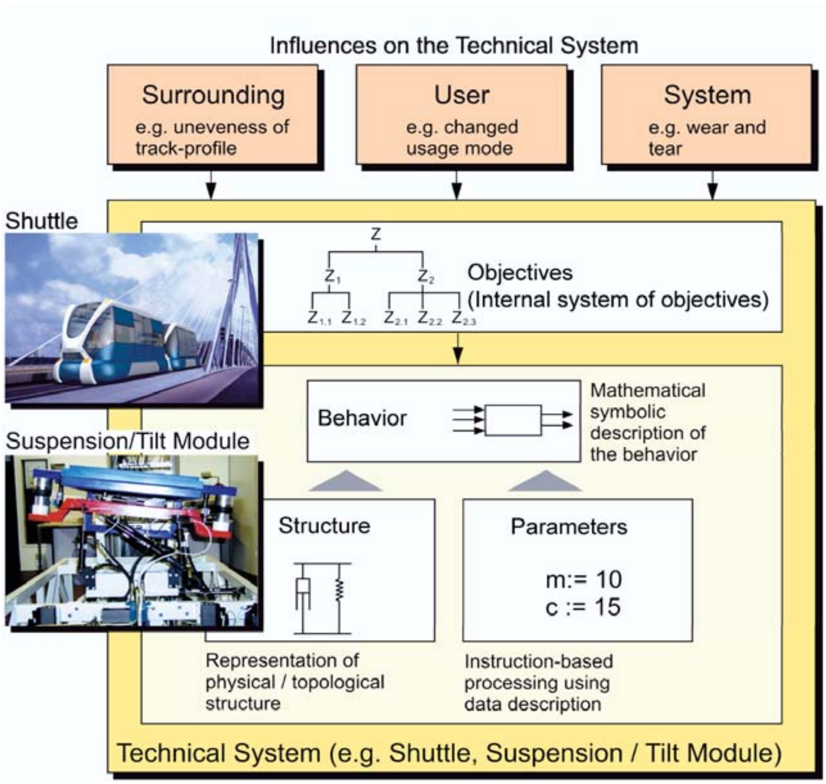

Fig. 1: Aspects of self-optimizing systems

1. **Analysis of the current situation**: Here the current situation includes the state of the system itself and all the observations that have been made about its environment. Such observations may also be made indirectly by communicating with other systems. The current state of the system also includes any records of previously made observations. One essential aspect of this analysis is examining the degree to which the pursued objectives have been fulfilled.

2. **Determination of the system objectives:** The current system objectives may be determined by selection, adaptation or generation. Here a selection is understood as choosing one alternative from a fixed discrete finite set of possible objectives, while the adaptation of objectives describes the gradual modification of existing objectives. We speak about generating objectives when new objectives are created independently of the existing ones.
3. **Adaptation of the system behavior**: This is determined by the three aspects: parameters, structure and behavior. The reaction at the end of the self-optimization cycle is effected by adapting the system behavior. The individual adaptation cases may be extremely diverse depending on which level of the mechatronic system we are dealing with. The domain in which the adaptation takes place also plays a considerable role.

From a given initial state the self-optimization process passes, on the basis of specific influences, into a new state, i.e. the system undergoes a state transition. We refer to the influences that trigger a state transition, as events. The self-optimization process defines the activities, that effect this state transition, and thereby describes the system's adaptive behaviour.

3 Representation of a Self-optimizing System

In order to describe the principle solution of a self-optimizing system, a set of domain-spanning specification techniques is used. Each specification technique constitutes a different view on the self-optimizing system. Each view is mapped by computer onto a partial model. The principle solution is made up of the seven partial-models: requirements, environment, system of objectives, functions, active structure, shape, application scenarios and the group behavior. Behavior consists of different types of behavior-models for example activity-diagrams, state-diagrams, multi-body-systems for motion-simulation, and block-diagrams.

There are relations between these partial-models, leading into an integrated system of partial-models that represent the principle solution of a self-optimizing system. The partial-models are created during the conceptual design [4].

For the application of the evolutionary algorithm the representation has to be distinguished between two forms: The genotypical and the phenotypical representation [11]. In the genotypical form of representation, the system is represented by an active structure, expressing the system elements and their interactions. The phenotypical representation consists of the partial-models function, shape and the multi-body-system (for motion simulation) plus a block-diagram of the group behavior. Figure 3 shows an example of the phenotypical and genotypical representation. The latter is shown by an example of a multi-body-system. The evolutionary algorithm creates the genotypical representation automatically, following the principles of the natural evolution. The phenotypical representation is used to evaluate the created solution. It is derivated out of the active-structure automatically. This approach provides fundamental partial-models of the principle solution: The active structure, the functions, the shape, the multi-body-system and the block-diagram. The benefits of this approach are:

- The consistency of the partial-models is checked.
- The functionality of the represented system part is proved.
- The developers only have to develop and specify the unprovided partial-models.

This chapter explains the genotypical and phenotypical representation and the derivation of the functions, the multi-body-system, the block-diagram and the shape out of the active structure.

3.1 Genotypical and Phenotypical Representation

As mentioned, the active structure is used here as genotypical representation. It is modeled by system elements and the relations between them. We distinguish between material-, energy-, and information-flows and logical relations. At the beginning of the design process the system elements are still abstract and serve as substitute symbols for software components and assembly units. During the development process they are concretized. In order to define relations between the system elements, every system element has different interfaces. The magnitudes of the system elements (e.g. force, switching signals) operate via these interfaces. For a closer definition, four attributes are used: There is the interface-class (material, energy, information), the interface-type (e.g. mechanical), the interface-entity (e.g. newton) and two boundary values (min./max.). The interfaces can be directed or undirected, as well as input and output. The computer-internal representation of the system element contains references to partial-models. The partial-models describe the system element more exactly. For example Figure 2 shows a section of an active structure (simplified).

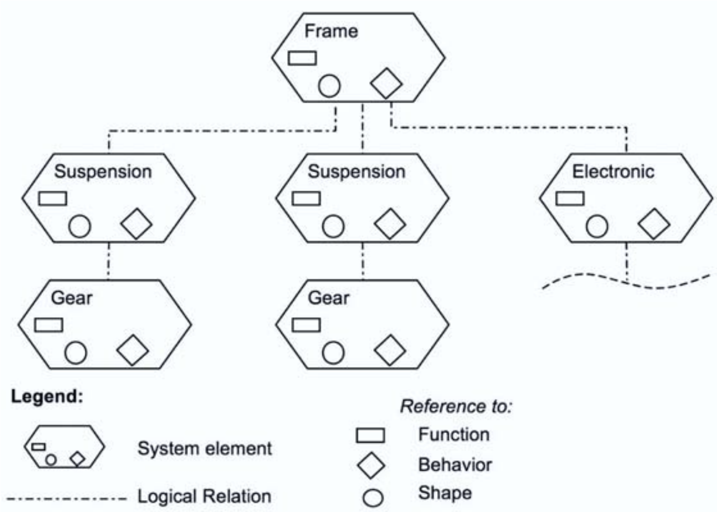

Fig. 2: Section of an active-structure

The partial-models function, shape, and the behaviour models multi-body-system and block-diagramm describe the phenotypical representation. The shape contains information about the rough shape of the elements, positions and arrangements, plus the types of active surfaces and points of action for logical functions [12]. The functions define the basic functionality of the system. For the design with evolutionary algorithms, special functions, according to Roth [13] are used. The behavior-models multi-body system and block-diagramm describe the controlled movement of the system [14].

3.2 Aggregation of the Phenotypical Representation

The phenotypical representation can be aggregated automatically out of the genotypical representation. Therefore each system element of the active structure is concretized by references to the system element specific partial-models functions, shape, and the behavior-models multi-body-system and block-diagram. During this transformation the partial-models referenced in the system-elements will be aggregated: An assembly-structure is aggregated out of the single shape-models, as well a function-structure is aggregated out of the functions and a overall multiy-body-system is aggregated out of the single multi-body-systems. At least a whole block-diagram, representing the controller, is aggregated out of the single block-diagrams.

The basic principle for the aggregation is the same for every kind of partial-model. The active structure represents system elements and the relations between the system elements. The relations are described via their material-, energy-, information-flow and logical relations. As a result of the interfaces and the relations between the system elements, relations between the partial-models can be derived.

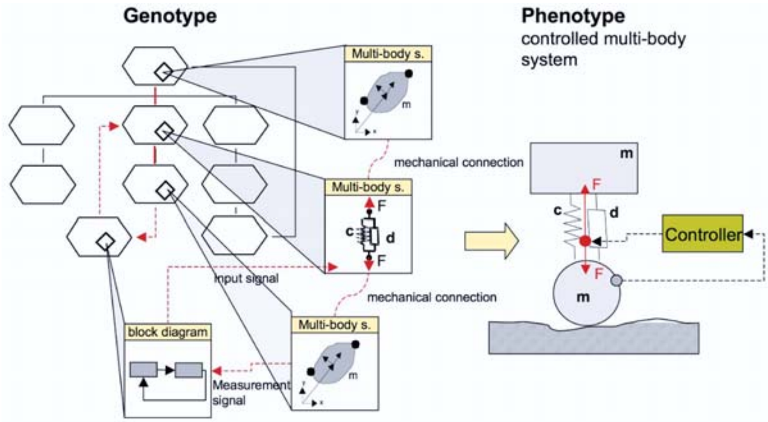

Fig. 3: Aggregation of a multi-body system with controller out of the active structure. Here only the multi-body-system is shown as phenotype.

The principle is shown in figure 3 by the aggregation of a multi-body system. In the figure, three system elements are connected via a mechanical relation - another system-element via an information flow. Every system element contains a reference to a behavior model: To a multi-body-system or a block-diagram. For example, the multi-body systems consist of two rigid bodies and one spring- and damping-system. Due to the formal connection between these models, a formal connection between these two multi-body systems can be derived. In this way, the three multi-body systems can be aggregated to one single multi-body system, describing the whole system.

4 Evolutionary Design

The evolutionary design-process is separated into two steps: a pre-process and a runtime-process. During the pre-process, all of the information will be created, which is necessary to describe the design-objective. During the runtime-process, the evolutionary algorithm creates the partial-models active-structure, functions, shape and the behavior-models multi-body-system and block-diagram. The procedure is shown in figure 4 in the form of a phase-milestone diagram.

4.1 Pre-process

The pre-process enfolds the five following steps: Definition of requirements, creation of a function-hierarchy, compatibility analysis, specification of motion and creation of an initial population. The first two steps are well known steps according to Pahl and Beitz and will not be explained here.

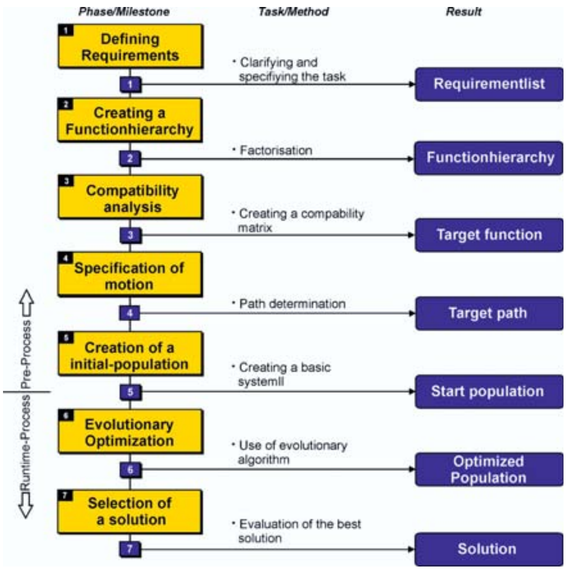

Fig. 4: Representation of the procedure as a phase-milestone diagram

The compatibility-analysis is executed with the help of a compatibility matrix. The requirements are specified in the lines of the matrix, whereas the functions are specified in the columns. It will be evaluated in the arrays, how well or how badly a function contributes to the fulfillment of a requirement. The scale goes from 1 (= basically incompatible) to 5 (= strongly supporting). The compatibility-analysis defines a relation between the functions and the requirements.

In the next step, the motion of the system is specified by one or more pathes. The system must be able to follow the pathes.

After that the initial population is created. It is described by active structures. The initial population is created randomly. Therefore the solutions are of low quality. The initial population is the starting point for the optimization procedure of the evolutionary algorithm. Before the initial population can be created a starting active-structure has to be developed. The starting active structure can be prepared in two ways. Either the user has already got an idea, of how the future system might look. Then the user specifies an active-structure, afterwards these will be multiplied and individual system-elements of the structure will be exchanged. If no idea is available yet, a system can also be created by random.

4.2 Runtime-process

In the following, the initial population is be optimized by an evolutionary algorithm. The procedure of the algorithm is generical: It enfolds the steps of evaluation, recombination, mutation and selection. These four steps run in an iterative process until a stop criterion is reached. The operations recombination and mutation, as well as the evaluation are adapted to this application and the description of the partial models. The algorithm is based on the genetic programming according to Koza [15].

Next, the steps of recombination, mutation, evaluation and selection are described in detail. Two new child active-structures are created via recombination from two active-structures. Now, two active-structures are selected randomly. In one of these active-structures, some interfaces are selected randomly, as well. The active-structure is cut at the selected interfaces. This results in two active-structure parts. In the second active-structure, all possible interfaces are determined, which, after the separation of the interfaces, result in a compatible active structure. For example, if two energy-connections and one information-connection are chosen in the first active-structure, all possibilities are chosen in the second active-structure, which generates two parts with two chosen energy-connections and one information-connection. From all possibilities, one is selected randomly. As a result, four sections of the active-structures are created. One section from the first active-structure will be connected with one section from the second active-structure. Thereby two new child active-structures are generated.

After this has happened, the mutation operation is used, to vary the active-structures. Thereby single system-elements and/or connections between them change. Which system-elements and connections change is decided at random. After the mutation, the active structure is evaluated. Therefore the phenotypical representation is used. The assembly-structure, functions and the behavior-models are aggregated from the active-structure. These models are analyzed and evaluated separately. After the evaluation a level of fitness[1] is generated.

The assembly structure is checked for collisions and whether all active surface pairings are consistent. In the function structure the connections between the individual functions are checked on whether the contained func-

1 The fitness is a value that describes, how well a solution corresponds to the requirements

tions are compatible with the requirements. The behavior is simulated and the movement process is recorded. The recorded path is compared with the pre-defined path and the deviation is evaluated. Moreover, the control-loops in the behavioral model are looked up and evaluated.

A standard practice is used for the selection: The rank-based selection. Thereby all solutions are sorted into a ranking list according to the level of their fitness. The higher the rank, the higher is the probability that the solution is going to be kept for the next iteration-loop.

5 Results

Three separate software tools were created to test the procedure: The tools are the “Genetic Designer”, the “Genetic Optimizer” and “VxDynamic”. The tool “Genetic Designer” can be used to specify an active structure. “VxDynamic” can be used for the graphical representation of the assembly-structure and the multi-body system, as well as for the analysis of the assembly structure and the simulation of the multi-body system. The tool “Genetic Optimizer” is in the center of the system. It implements the evolutionary algorithm, as well as the whole processing. The three tools can communicate via an XML-Interface. Until now, 89 different system elements are specified and saved as an XML-File.

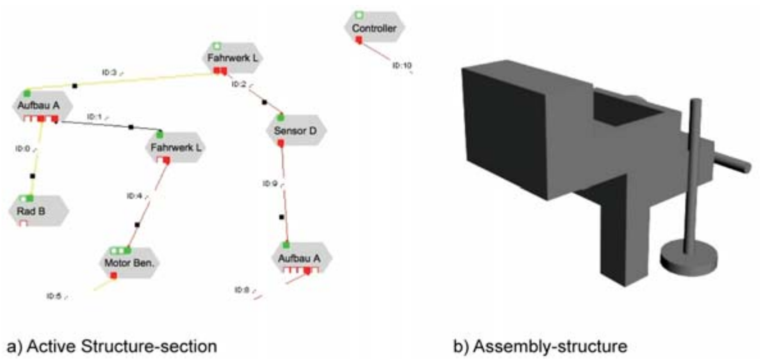

Fig. 5: a) Section of active structure and
b) assembly structure of the initial system

As application example a system from the area of automotive engineering was created to evaluate the method. From the 89 saved system elements, only 32 were suitable for the development of a vehicle. The vehicle should follow a predefined path. Additionally, some other requirements were given, too. These were for instance the dimensions of the vehicle, the weight, the acceleration rate and the maximum velocity of the vehicle.

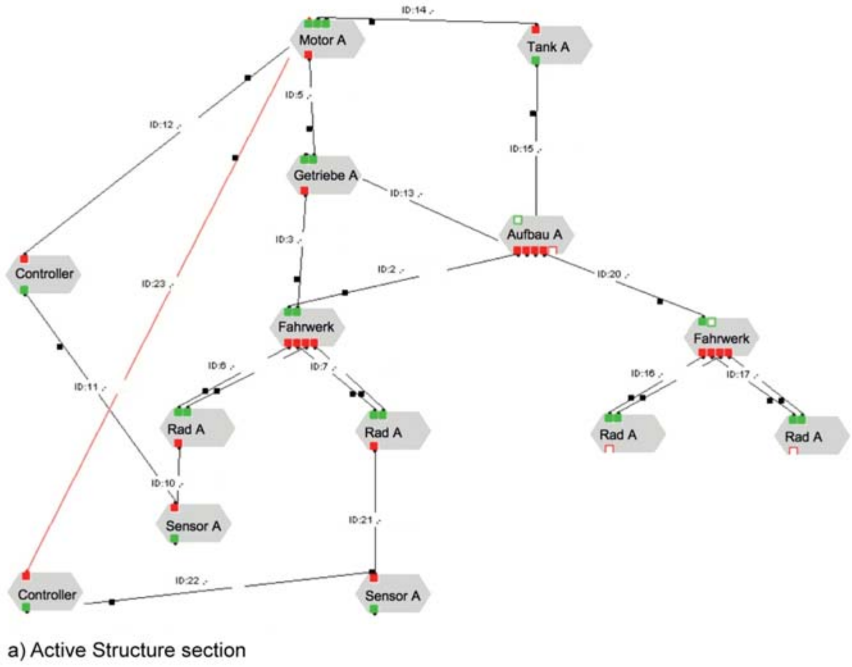

Fig. 6: Final active-structure of the principle solution

As starting point an initial system was created randomly. It consists of 21 system elements. All elements together do not result in a meaningful solution. Figure 5 shows a section of the active structure and the assembly structure.

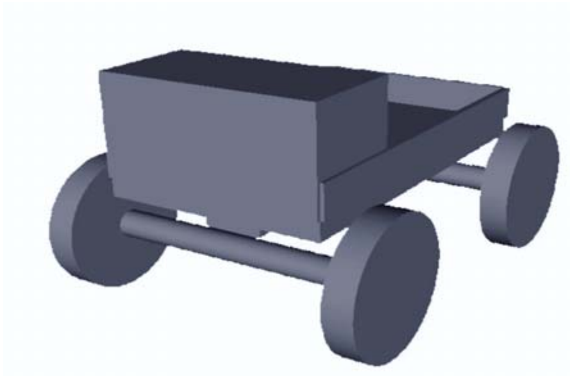

Fig. 7: Example of a final assembly structure

After 250 iterations, the process was stopped. Figure 6 shows the final active structure. The solution is a vehicle, consisting of 14 system elements. It fulfills all requirements and it is able to follow the predefined path. Figure 6 shows the final assembly-structure. The picture shows a rough shape of the designed solution. Apart from the shown active-structure and assembly-structure (Figure 7), a function-structure, a multi-body system, and a block-diagram are created.

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Case Study of a MEMS Switch Supported by a FBS and DFM Framework

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Abstract
This paper presents the work on a collaborative and integrated design approach that supports the product solution emergence by least commitment. That design framework is based on several engineering activities that must be achieved concurrently. The first depicted activity aims at mapping product requirements to product breakdown based on FBS approach. The second one supports manufacturing information synthesis during the design process (i.e. DFM). The second part of the article presents the design of a Micro Electro Mechanical System switch to illustrate the whole design method. That example illustrates the information modelling previously presented and shows how the CAD model emerges from information synthesis during the design process. That example also allows the consolidation of the product modelling. In a second time, it shows that the method fits to the design of micro product and provides to the designers early behavioural analyses.

Keywords
FBS, DFX, MEMS, Design Framework

1 Introduction

During the last fifteen years, the design process has turned into a collaborative and a simultaneous process. It involves plenty of different engineering experts who must communicate, exchange pertinent and understandable information. This complex process is still the subject of improvements and full of research objectives. One of the limits of the current approach is the importance of the 3D geometry provided by CAD software. Design experts have to work with an initial CAD model but can not really participate to the emergence of the solution. Moreover the information flow is often broken: it is difficult to justify the different choice (who, why, when).

The collaborative and integrated design approach that is presented in this paper supports the product solution emergence by least commitment and actually considers the geometry as the final result of the design process. The product solution emerges from the integration of the design experts constraints and allows the continuation of the information flow. To assist engineers in deploying that design approach, information modelling is presented in three main categories (cf. fig 1):

- **Collaborative information sharing:** manages, protects the data and allows the different designers to share and access the pertinent and reliable information as soon as they are available.
- **Experts' engineering modelling:** supports data of the design solution to assess the X'ability of the product according to specific engineering activity (mechanical analysis, manufacturing, etc.).
- **Interface modelling**: supports the link between experts' engineering modelling and collaborative information sharing (i.e. support for synthesis). Those models aim at supporting the CAD model emergence by least commitment.

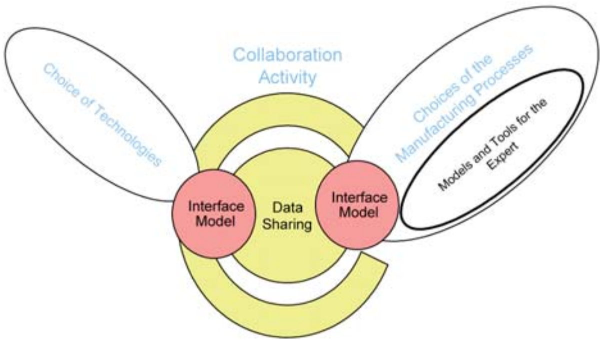

Fig. 1: Overview of the Integrated Design framework

The first section presents the product modelling concepts. Two engineering activities are presented: the mapping between functions and technologies via physical principles, and the selection of potential manufacturing processes. At last interface models which link engineering expert modelling and the collaborative information sharing is detailed.

The second section is an illustration of the approach through the design of a Micro Electro Mechanical System (MEMS): an electrical switch. The interest of such an example is to open the application field, to show the generic aspect and the limits of the design approach.

2 Integrated Design Framework

The presented design process (cf. fig 1) is based on multiple iterations of analyse/synthesis done by each design expert: the data sharing core communicates, through the right interface model, the information to specific engineering models; as soon as the expert activity is done, a specific interface model return the data into the data sharing core.

2.1 Collaborative Information Sharing

The data sharing core shares information related to three domains:

- *Product* information: results of the design process.
- *Design process* information: organisation of activities and resources.
- *Industrial organisation* information: definition and leading of projects and performance indicators.

It manages and set relationships among information from the different design expertises [1]. It is then possible to notify potential conflicts and warn the concerned experts. Then those involved experts will start the discussion to find a solution.

2.2 Design Experts' Engineering Modelling

Figure 2 presents how can be detailed expert activity in the global integrated design framework:

- *Simplified models* support data to allow rapid analyses of the expert activity (DFX concept) in order to propose a large number of alternative solutions as soon as possible in the design process.
- *Advanced models* are made for product accurate analyses and to find the "best" solutions among alternative ones. They usually need more time and information than the simplified ones. They are therefore used later in the design process.
- The *knowledge base* represents any kind of knowledge (ex: books, computer database, own experience, etc.) used by design experts to find solutions respect to specific requirements.

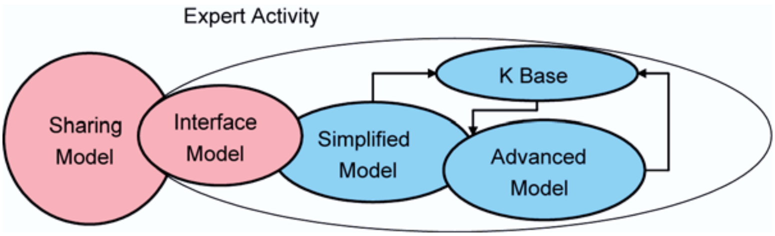

Fig. 2: Details of design expert activity

Technology Selection Activity

Concerning the selection of technologies and the early assessment of the solution behaviour, several models have been proposed in the literature. Triz [2] method links the functions to the technologies, but is not integrated in a product model. It does not propose formal (parameters) justification of the choice (least commitment) and is not link to behavioural simulation methods. It can be assimilated to the proposed knowledge base (cf. fig 2).

Bond Graph [3] model represents multi physical system through energetic flows and, thanks to its formalism, behavioural simulation can be done very early in the design process. Unfortunately, there are no links between the functions and the associated technologies, and it does not provide methods to find alternatives solutions. This model could be seen as an interface and simplified model (cf. fig 2).

Function-Behaviour-Structure [4] method links the function, the behaviour and the structure and makes emerge different sort of parameters (functional behavioural and structural). It is a simplified model (cf. fig 2).

Based on those models the authors propose a Function, Physical Principle and Technology (FPPT) model. It is partly based on the former models and adapted to our design context (cf. fig 3).

- A *Function* describes what the product is designed for. It comes directly from functional analysis. A Function can be decomposed in two or more Functions or be redefined in order to refine its description. Some parameters are attached to it.
- A *Physical Principle* (i.e. physical law) is the link between a Function and a Technology. It has parameters which come from its definition. It might also have some limits: due to the scale or due to another physical law. A Physical Principle can be affected by an energetic loss; such loss is also notified in the description of the Physical Principle. [5] also propose the use of physical principle in the design process.

- A *Technology* realises a function trough a structure. Some parameters are also linked to it. They come from the behaviour and the structure of the technology. The technology might have some limits due to the scale or the technology itself.

The role of the different parameters (functional, physical and technological) is to allow behavioural analyses at the beginning of the design process, when no geometry is available. Parameters and the physical laws can be exported to any simulation software (such as matlab) to provide a first evaluation of the chosen physical principles and technologies.

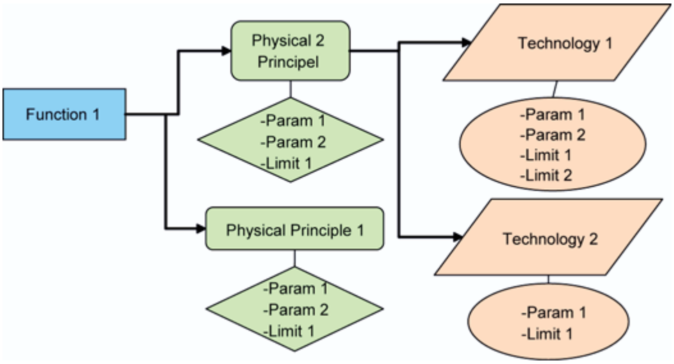

Fig. 3: Overview of the concepts of the FPPT Model

Selection of Manufacturing Processes

The proposed expert activity which concerns the selection of manufacturing processes (DFM) is based on [6]. A processes database is used to identify alternative solutions based on design requirements. In the proposed analysis/synthesis approach, each process alternatives is then linked to one product alternatives constrained by manufacturing technological and physical limits.

2.3 Interface Modelling

Interface models (cf. fig 1) allow the continuity of information along the design process and among expert activities. In our approach those models are based on flow description using *skin and skeleton* concepts. As previously introduced, interface model also aims at supporting geometry emergence by exchanging information from expert activity to information sharing model. The authors have then based this model on flow description.

Skin and skeleton concepts introduced in [7] and [8] have first been used by the authors to represent generic flows (section, trajectory and envelope surface). Then two kinds (i.e. multiple representations) of specific skin and skeleton have been detailed: *usage* (design specification) and *manufacture* [9]. Those two interface models respectively represent energetic flows related to physical principles (FPPT model) (cf. fig 4) and material flows related to manufacturing processes (DFM activity) (cf. fig 8).

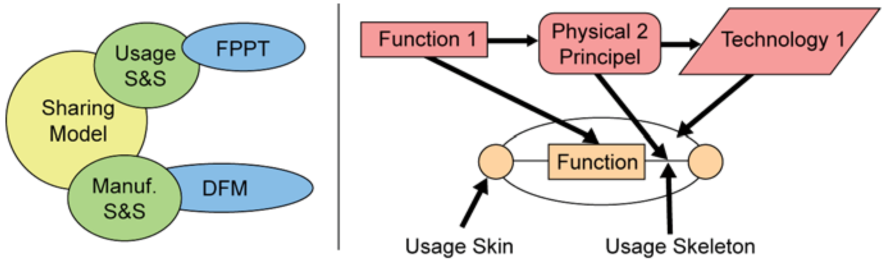

Fig. 4: Usage interface model respect to FPPT modelling

In the continuous analysis/synthesis process as presented in this design framework, Usage skins and skeleton issued from FPPT modelling are identified as requirements for manufacturing processes selection (cf. fig 4) that afterwards provides manufacturing skins and skeleton. Those skins and skeletons (section, trajectory and envelope surfaces) progressively support the emergence of the CAD model by least commitment (cf. fig 6).

3 Design of a MEMS: Electrical Switch

An electrical switch has been chosen in order to assess this design method on micro products. [10] noticed a lack of MEMS design methods especially during the embodiment design. Switches are relatively simple systems and representative of MEMS and more generally micro-system. Furthermore, there already exists a huge variety of them, each MEMS design company bring their own products. This example is based on the switch presented in [11]. It is called a “beam switch” since a beam establish the contact via a deflection induced by actuating electrode. It uses an electrostatic strength.

3.1 FPPT Modelling

The starting point for technologies selection is the functions that the final product must fulfil. The three main functions are:
- allow an electrical current
- not allow an electrical current
- switch between the two previous functions

To allow or not an electrical current through the switch, the physical principle is the conductivity of materials. So the associated technology just concerns the properties of materials. Two functions have emerged from initial switching function. The first one is that a movement must be possible. This function is done via a deformation (Hook law), the technology concerns the geometry and the material. The second function is that strength must be applied in order to have movement. It will be an electrostatic force created by electrodes. Figure 5 shows part of the FPPT model.

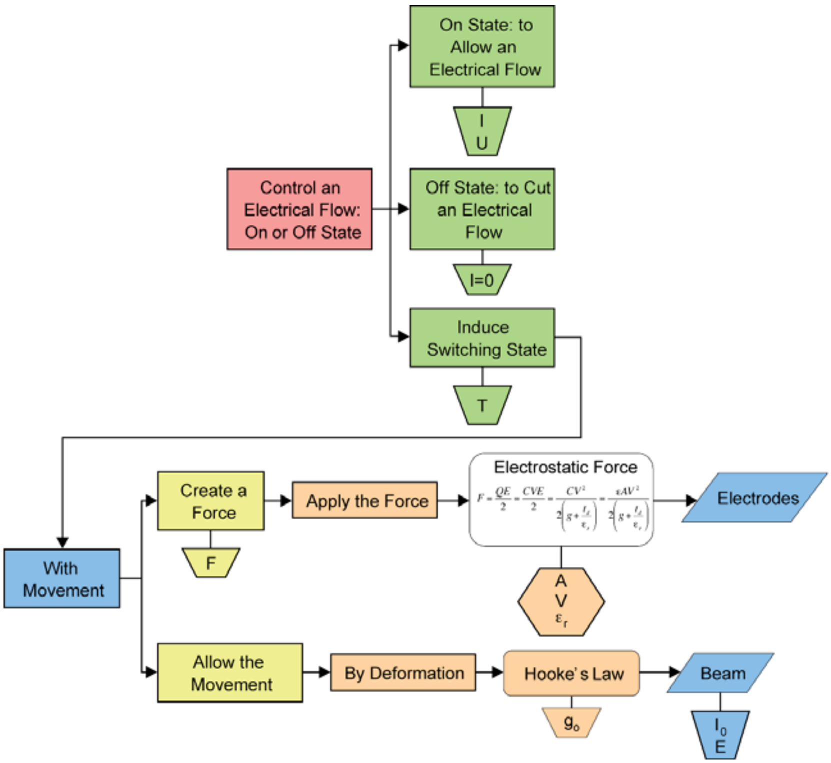

Fig. 5: Part of the FPPT model of the switch

3.2 *Usage* Skin & Skeleton Representation

Thanks to the final FPPT model, the usage skins (functional surfaces) and the usage skeletons (trajectory of the energetic flows in the parts) can be defined (cf. fig 6). On a macro scale, the roughness of the skin can be defined but such notion does not exist, or can be hardly defined for the micro scale. The usage skeletons are also more described. They can be more or less constrained. Here, the unique skeleton which is strongly constraint is the bending beam. Its definition will be driven by equations in order to have the right behaviour for the final solution.

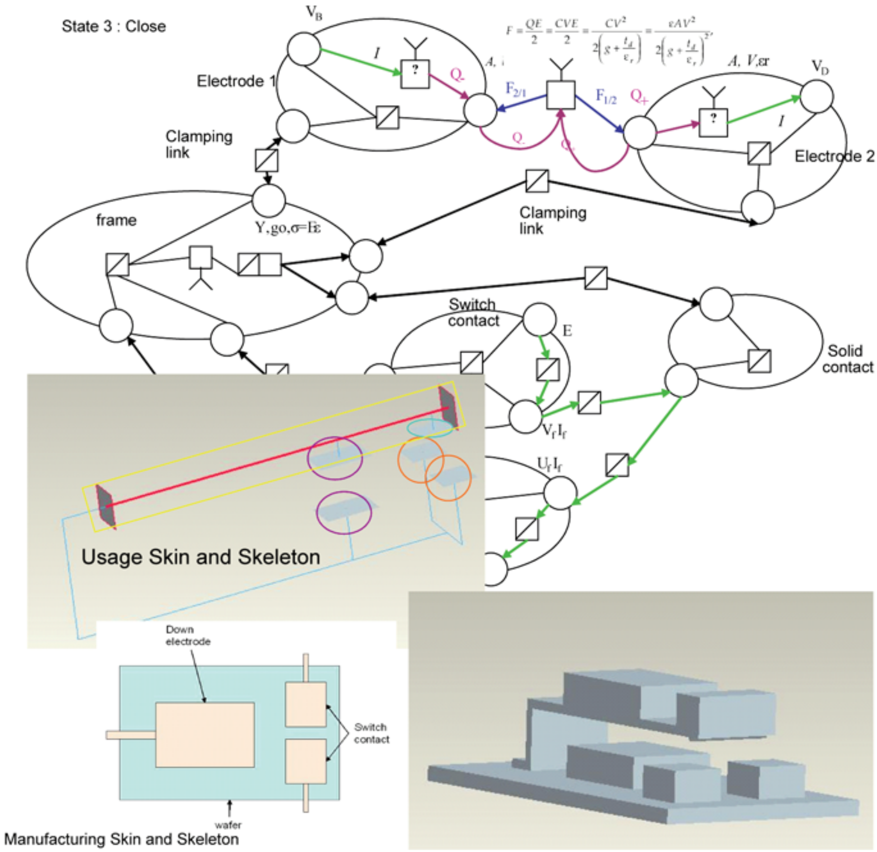

Fig. 6: Interface models of the switch toward the emergence of the CAD model

3.4 Selection of Manufacturing Processes

Most of the MEMS manufacturing processes come from the integrated circuit manufacture. Some MEMS manufacturing processes can be cited: microlithography, spark machining, micro surface machining, laser microsurgery. The chosen process is VLSI (very large scale integrated circuit) based: thin film deposition, photolithography and etching processes. The system will be built by successive layers which perfectly fit to the manufacturing skin and skeleton representation.

The first constraint given by the manufacturing process is in fact the wafer which reference plan must be parallel to the largest surface. This orientation is very important because all the entire structure depends on it. The electrodes are the largest surface and one of them is embedded in the beam, the beam orientation is defined. The next constraint is the thickness of the deposition layers. This gives information to build the skeletons which has to be proportional to this thickness. Another constraint is the material because the deposition material depends on the deposition process. Moreover we have to make sure that all materials are compatible to ensure good adhesion during deposition. Then the expert manipulates different manufacturing skeletons (cf. fig 7) in order to model the entire part that must include usage skins and skeleton (cf. fig. 6).

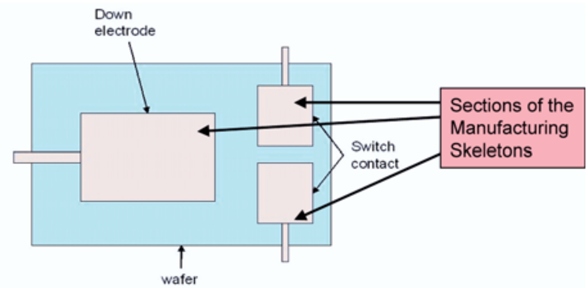

Fig. 7: First step of the process planning

4 Conclusion

This paper has presented the component and the process of a design framework. This framework is articulated around a sharing data core which allows the continuity of information among expert engineering models through specific interface models. The emergence of the solution by the synthesis of constraints from each design activity allows the product to be designed by least commitment. The presented FPPT model connects the functions to the associated technology through specific physical principle. Thanks to the different parameters, behavioural simulation can be done to have an early idea of the behaviour of a technology. A future work will focus on the creation of a connection with physical principle libraries developed in Matlab. Another objective is to propose a software demonstrator to support the FPPT modelling.

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Digital Processing and Fusion of 3D Data from Emerging Non-Contact 3D Measurement Technologies

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Abstract
In recent years, globalization has begun to drive industries to operate in a highly competitive environment and to improve the time to market. In order to deal with this challenge, rapid production methods have been developed and incorporated into many phases of the product life cycle. Reverse Engineering (RE) technology enables fast design based on an existing physical object, and on-line 3D non-contact inspection significantly reduces manufacturing time. This paper provides an overview of the state-of-the art in 3D emerging measurement technologies. Moreover, it proposes new approaches and methods for data fusion and digital processing of sampled 3D data.

Keywords
Non-contact measurement, reverse engineering, data fusion, digital processing, inspection

1 Introduction

A complete definition of a simple engineering part requires only a few measurements. These measurements provide the intrinsic parameters (i.e., lengths and angles) that uniquely define the basic shapes from which the part is constructed and the relative location of these shapes. In the case of freeform objects, however, the situation is completely different. Since no prior information about the object's shape is available, it is impossible to pre-determine the required measurements. Therefore, in order to capture the shape of a complex object accurately, a very large number of measurements are needed, and these cannot be acquired feasibly using traditional CMMs.

Fortunately, recent advances in computer vision and optics have led to the production of a variety of non-contact scanning devices, which are capable of sampling very dense clouds of points from an object's surface in a reasonable amount of time.

2 Three-Dimensional Non-Contact Measurement Technology

Non-contact 3D measurement is a rapidly growing field. This paper discusses in detail the following emerging technologies: laser scanners, lasers based on Conoscopic Holography technology and 3D cameras (Figure 1).

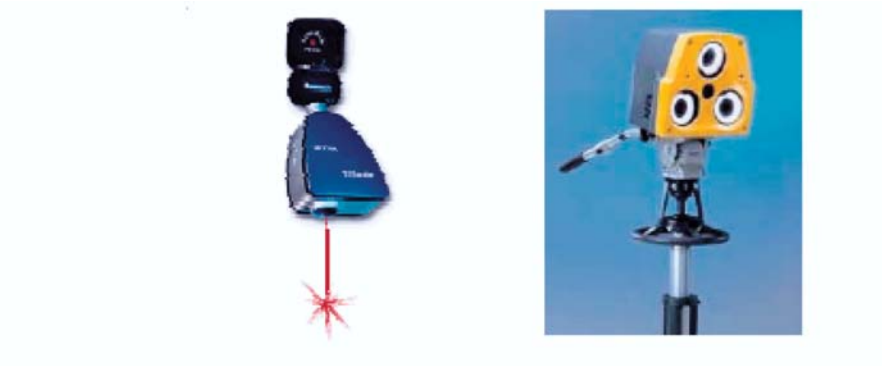

Fig. 1: A scanner laser [12] and a 3D camera [5]

Laser scanners: Most contemporary non-contact 3D measurement devices are based on laser range scanning. The simplest devices [6] are based on the laser triangulation technique. This is an active stereoscopic technique in which the distance of the object is computed by means of a directional light source and a video camera. The CCD camera's 2D array captures the image of the surface profile and digitizes all data points along the laser. The disadvantage of this method is that a single camera collects only a small percentage of the reflected energy. The amount of collected energy can be drastically increased by trapping the entire reflection cone [11, 12], thus significantly increasing the precision and reliability of the measurements.

Lasers based on Conoscopic Holography technology: Conoscopic Holography [15] is a simple implementation of a particular type of polarized light interference process based on crystal optics. In the basic interference set-up, a point of light is projected onto a diffuse object. This point creates a light point, which diffuses light in every direction. In a conoscopic system, a complete solid angle of the diffused light is analyzed by the system. The measurement process retrieves the distance of the light point from a fixed reference plane. The problem inherent in laser scanning is its relatively low measurement speed, though it is faster than traditional contact Coordinate Measurement Machines (CMMs).

3D cameras: 3D photography is based on reconstructing 3D data from 2D images, taken from different points of view (stereo-photography). The basic problem with this approach is the correspondence problem. In 3D cameras a pattern is projected on the object and the same pattern points are identified on each image [5]. This approach is much more efficient, since it does not require marking specific points, and it can produce a very large number of measurements in one shot of the camera.

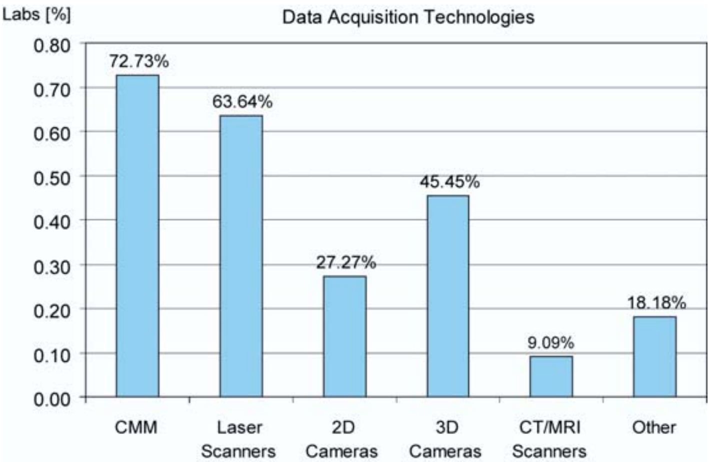

Fig. 2: Distribution of 3D scanning technologies among 23 engineering universities and research centers across Europe

As part of our previous research [8], industry requirements were determined in virtual manufacturing and rapid production fields. The research investigated 24 research groups from universities and research centers and 10 industries that develop or use non-contact technology.

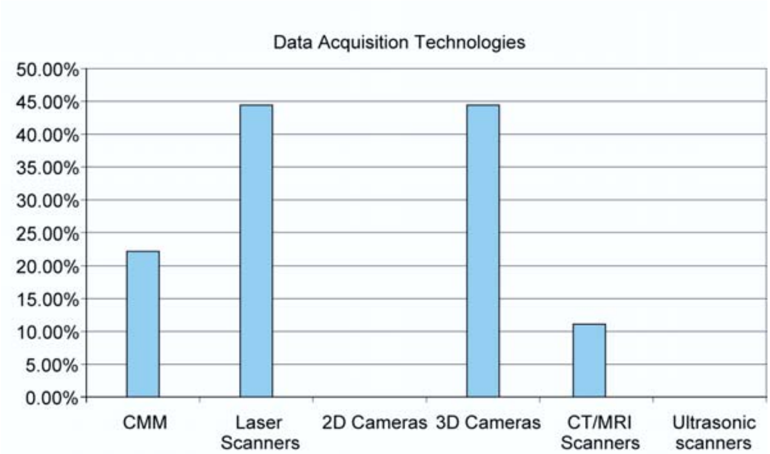

Fig. 3: Scanning technologies used/developed in industry

The following figures provide examples of such analyzed data. Fig. 2 depicts the distribution of 3D scanning technologies among engineering universities and research centers. The figure shows that contact CMM is still a prevalent 3D measurement device. The graph in Fig. 3 shows the scanning technologies used/developed in industry, and the graph in Fig. 4 describes the use of diverse scan data in industry.

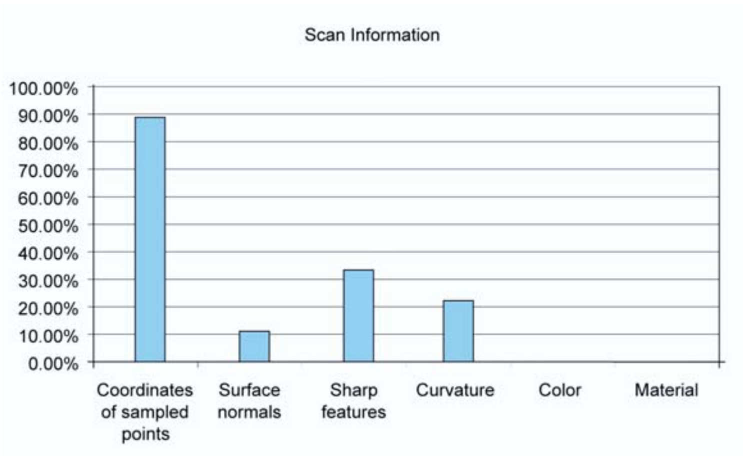

Fig. 4: Use of diverse scan data in industry

3 Applications Utilizing Non-Contact Scanning Technologies

Traditionally, the major users of 3D scanning technology were the automotive and aerospace industries, primarily because freeform surfaces often appear in the parts produced by these industries. As this technology becomes more affordable, however, its applicability in other fields is gaining recognition. Recently it is becoming clearer that the best solutions can be produced by combining several scanning techniques. We expect that in the near future, 3D technology developers will be encouraged by users to cooperate in order to produce more comprehensive, fast and reliable solutions.

Recently 3D scanning technologies have begun to be used in many phases of the product life cycle. Figure 5 shows the distribution of 3D scanning usage among members of research institutes across Europe [8]. The figure shows that most of the users have incorporated the technology in the design and manufacturing phases, mainly for purposes of reverse engineering and redesign. While the technology can also significantly improve inspection, most users still prefer conventional contact CMMs. This finding suggests many opportunities for introducing novel non-contact measurement techniques into the inspection phase of the product life cycle.

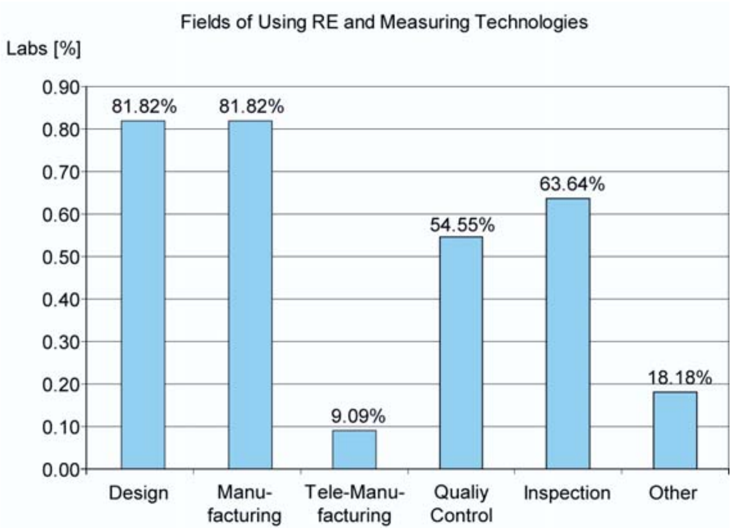

Fig. 5: Distribution of 3D scanning usage among universities and research centers

4 3D Data Processing

To process 3D digitized data, contemporary CAD systems supply reverse engineering modules. These modules, however, require considerable designer intervention to achieve an accurate resulting model. A typical surface reconstruction process consists of the following steps: (a) triangulation of the data points; (b) semi-manual segmentation; and (c) surface fitting. For each mesh segment, the system fits a smooth analytic patch and stitches these patches along boundaries. Yet meshing the cloud scanned from a complex object can cause some difficulties. Moreover, the point clouds are often incomplete and noisy, making the meshing process highly unstable. Figures 6a and 6b present used/developed reconstruction methods.

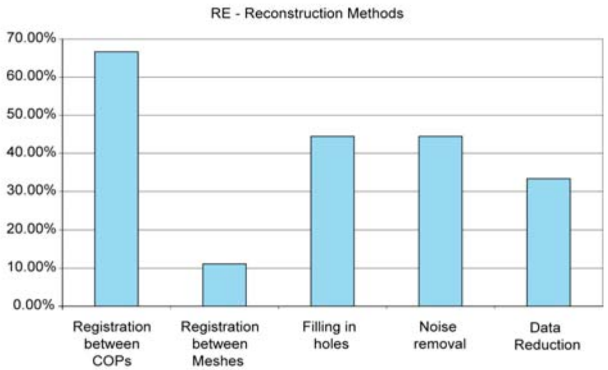

Fig. 6a: Used/developed reconstruction methods in industry

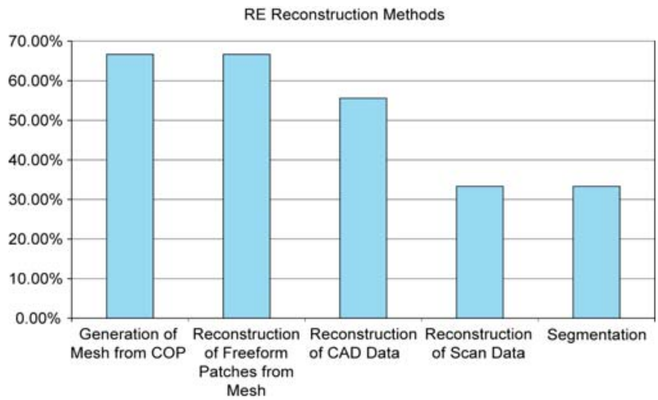

Fig. 6b: Used/developed reconstruction methods in industry

Although commercial RE modules are evolving rapidly, there is still a gap between the proposed tools and industry demands. Such critical issues as efficiency and robustness are still the weak points of the existing solutions. These weaknesses prevent RE methods from being used for other applications, such as dimensional inspection.

In order to overcome these obstacles, we propose a new reconstruction approach to RE based on volumetric representation of the object's shape. The method is applied on scanned points of data: (a) reconstruction of volumetric implicit model from the scanned cloud of points, (b) geometric tensor field propagation, (c) anisotropic surface meshing, and (d) subdivision surface fitting. The scheme of the proposed method is demonstrated in Figure 7. In the following section, each stage is described in detail.

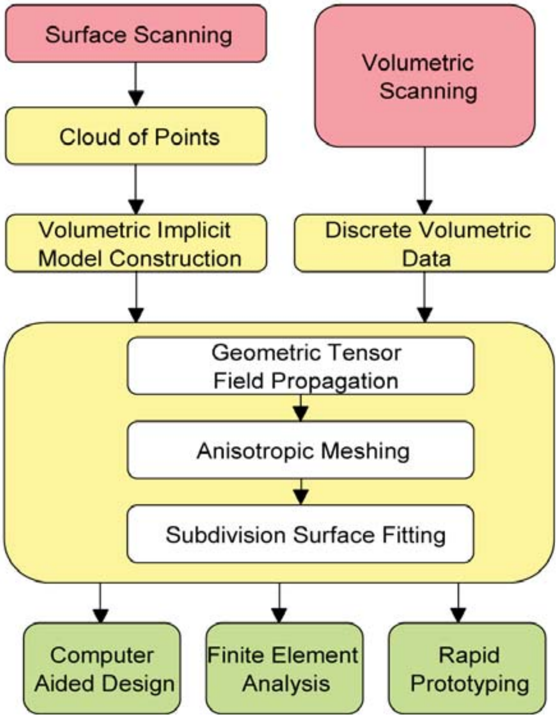

Fig. 7: A scheme of the proposed method

Reconstruction of volumetric implicit model: First, an implicit model is reconstructed from the scattered points, where a set of overlapping quadric patches is fitted to the points [13]. Then, these patches are blended in order to produce a piecewise-smooth implicit surface.

Geometric tensor field propagation: The geometric tensor field is evaluated from the implicit model. This geometric field is based on tensors of curvature of the implicit model and induced by the desired object's shape, so that the problem domain becomes anisotropic.

Anisotropic surface meshing: In order to extract an explicit representation of an object, the implicit model is meshed. Since the meshing is performed in the anisotropic space, the resulting polygonal mesh is adaptive and exhibits anisotropic properties of the object shape.

Subdivision surface fitting: The surface reconstruction process is resumed by fitting a subdivision surface to the implicit model, while the adaptive mesh is used as a control polyhedron. The fitting is performed iteratively using the quasi-interpolation method [10].

The proposed approach has the following advantages: (a) An implicit model of complex shapes can be robustly reconstructed from noisy or incomplete clouds of points with non-uniform density. (b) Anisotropic meshing produces high quality, quad-dominant meshes. These meshes are very suitable for modeling and analysis applications. (c) Subdivision surfaces can be automatically generated from the anisotropic polygonal meshes. The major drawback in the current implementation of the proposed approach is that the size of the adaptive grid is defined *a priori* by the user. In addition, the proposed adaptive method requires significant computational effort. Since the most expensive computations are local, and therefore can be easily parallelized, we see great potential in implementing the proposed method on parallel machines. This work has demonstrated one of the promising directions towards more robust 3D shape processing utilizing emerging non-contact scanning technologies.

5 Summary and Conclusions

This paper has investigated existing non-contact scanning methods and processes used in industry and research centers for product development. Following are the conclusions: (a) Part geometry has become complex. As a result, thousands or even millions of points are required to accurately model geometrically complex parts. CMM technology is not suitable for such parts. (b) New materials are constantly being introduced in today's products. Measuring the surface of flexible or fragile parts with a CMM can lead to indentation, thus reducing the overall accuracy or damaging the part. (c) Currently, there are two major applications for 3D scanning technology, reverse engineering and redesign. Gradually, however, the focus is being shifted to the inspection field. (d) The use of diverse data is hardly noticeable, though it is available via non-contact technologies. The above discussion also refers to the reconstruction process. The proposed new reconstruction approach, based on a volumetric representation of the object's shape, can be integrated with non-contact technology. The meshes are suitable for modeling, simulation and analysis applications.

6 Acknowledgments

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3D Digitalization for Patrimonial Machines

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Abstract
Nowadays, digital document is becoming the standard way of working: travellers have lighter bags but mainly transmission of such documents is faster, and their use is far more convenient to search into them. Consequently, digitalizing physical paper is also very common: many people own a scanner at home. But what about objects? 3D artefacts also need to be digital. CAD software is nearly always used by enterprises for designing their product. But what about old objects, old machines, 100 years older or even more? These basics of technical knowledge have also to be digitalized. 3D scanning technologies are fully emerging in Industrial Engineering. Our scientific researches are targeted on old objects issued from heritage. We propose to virtualize them. But 3D scanning technologies need to be customized as we are working with patrimony where sometimes it is impossible to lighten the object or to move it. The aim of this communication is to define a methodology using a decision tree with adapted operators for digitalizing old objects respecting patrimony conditions. In addition, we illustrate our research with two examples where it has been used digitalizing technologies.

Keywords
3D digitalisation, CAD, heritage

1 Introduction

Nowadays, the situation of the technical and industrial heritage points out many problems: how to manage and valorize it in case of Museums and sites? How to ensure life prolongation for the technical information of the collections, archives and heritage places? This technical information, testimony of the past, are becoming older very fast; like a puzzle which parts wear or disappear, the technical data dispel progressively with the time. That is why preserving the national technical patrimony has now become a priority for governments and world organizations. As saving and maintaining physical object cost a lot for museums, and sometimes dismantling is impossible because the machine falls into ruin, our approach proposes a new kind of finality witch is to preserve it as a numerical object

In the first part of this communication, we explain why preserving objects under a numerical form can be a solution for museums; we expose the global developed methodology that merges Industrial Engineering Sciences and Social Sciences. Next, a state of the art and a classification about the 3D digitalization tools are established. Finally, we illustrate our gait with examples.

2 The Protection of the Scientific, Technical and Industrial Heritage

The protection of scientific, technical and industrial heritage is a rather recent idea. It is in England during the Sixties, that was born what British people call the "industrial archaeology". The first experimentation object for the capitalization and the valorization of the heritage was the Ironbridge (it was the first iron bridge, built in 1779 and classified to the world heritage of UNESCO in 1986) (Rolland 2001).

Initiated in 1992 by the French culture and communication Ministry, the French research and technology Ministry and the French Education Ministry, the REMUS project was the first one that had developed interdisciplinary teams in order to find new solutions for the museology of sciences and technology. Several works and studies were finalized: the main target was to give advises when using audio-visual technologies (Remus 1993). But, in term of museology, no new didactic methods have been developed since 1992.

In 2003, at the ICHIM conference, Jean-Pierre Dalbéra from the French culture and communication Ministry stressed on the need for a capitalization and a valorization of the French heritage (Dalbéra and Foulonneau 2003).

Since this communication, many research programs have been started in France; among them, we can mention GALLICA and CNUM. However, those projects are focusing on historical documents, images, art objects or architectural monuments. The technical industrial heritage has not been targeted as a priority for conservation.

In its book "the objects life ", Thierry Bonnot, anthropologist, consigns that "an object takes a meaning only in a human context" (Bonnot 2002) . A machine or a system is significant only if it can relate a social act and helps to conserve all the aspects of a technical culture, i.e. the physical objects as well as the vestiges it contains: gestures, know-how, social relations... The studied object cannot be dissociated from its context (know-how, political context, social context, economical context...). Just like the photocopy gives back the object within its framework, the sound track on which it has been consigned, critical information for understanding the object or the written report on which the auditor has reported the human context, all those elements allow re-contextualisation of the object (Rolland 2001).

Depending on the desired finalities of the valorization, it will be recommended to capitalize all the necessary knowledge for achieving this goal. Thus, dealing with old technical objects, knowledge to be capitalized can be divided into two kinds: the object definition (the internal characteristics) and the outside world (the context definition).

3 Hypothesis and Methodology

3.1 Tools and Methods from Engineering Sciences

For capitalizing knowledge, many methods are used but it is not the goal of this communication. However, once the external knowledge captured, remains the problem of the physical object conservation. So as to resolve this problematic, engineering tools and more widely virtual tools and computer graphics can help.

As Olivier Lavoisy has demonstrated it in his thesis (Lavoisy 2000), evolutions of the technical drawing (he prefers to use the term: graphical techniques) are becoming really powerful since several years. Then, after numerous analyses, he raised the conclusion that graphical techniques are more than one hard copy: "graphical techniques seem to play a role in the transmission of know-how within the workshops, within the training centers and into academies".

Since the "Renaissance" until 1990, 2D paper was used. But in 1970, computers have been introduced into the industrial systems for helping workers. And next, Computer Assisted Design (CAD), Product Data Management (PDM), Digital Mock-Up, Virtual Manufacturing… Nowadays, digital mock-ups are used for replacing physical models. It is possible to carry out various functional simulations, to try various aesthetic design... Moreover, in virtual reality domain, tools have been developed so quickly that virtual simulations of dynamic situation are close to realistic ones.

If we consider the idea of starting from a real object until its virtualization, we can compare both status of the object (see figure 1). Once the object virtualized, it is called a digital mock-up or an artifact; however, if the real object is conserved or repaired, it becomes also an artifact as it is not the same as the original object. The main differences are that visualization of a virtual object can be adapted to the public targeted.

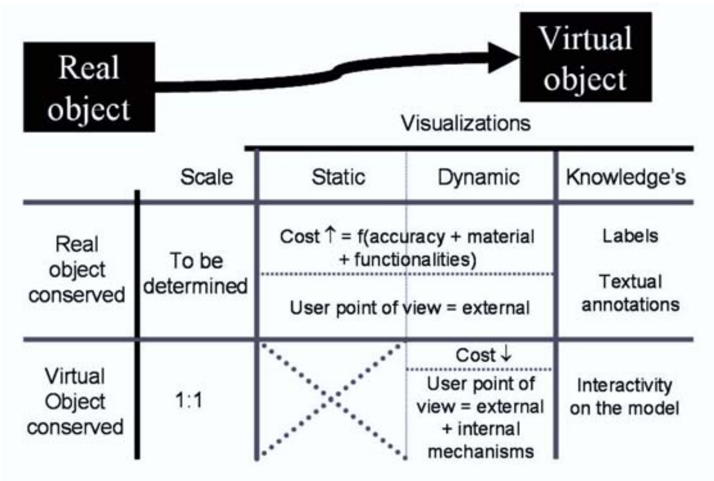

Fig. 1: Comparison between conservation of the real object and the virtual object

3.2 Virtualization Methodology

Before designing a virtual model, it is necessary to identify and capitalize the required information. Both internal and external knowledge have to be extracted as explained before. However, notice that the source of information, which is the most important, is obviously the object itself if it still exists. Consequently, picking up information on the object or its components gives more authenticity than extrapolating a drawing.

As presented in the previous sections, tools and methods from engineering sciences can give solutions for this new kind of capitalization. Issued from the industrial engineering, a new digital chain can be defined: first, capture physical and textual information's; next, design the 3D model and its dynamic; and finally, simulate Virtual Reality applications. In the following part of this communication, we will concentrate on the first step of the digital chain process: the object digitalization.

4 3D Digitalization

Answering to the problematic of patrimonial object digitalization, we give a state of the art of the different technologies that can be found on the market or new technologies issued from fundamental research that will emerge in the near future. We distinguish active systems and passive systems. The main difference is due to the technology used: emitting or not a light beam. Moreover, as we usually work with old objects, contact can be sometimes impossible or even forbidden (this will be explained farther late).

4.1 Systems with Physical Contacts

They are the basic measuring instruments that are used since a long time:

- decameter,
- slide caliper,
- micrometer caliper...

There are also many mechanical palpation systems that are nearly automatic and are usually combined with a canned jib for controlled by a computer. Some of them are named TMM for Three-dimensional Measurement Machines. But the most important difficulty is that the object to measure has to be brought in the laboratory, as those measurement systems are usually not movable. Moreover, they need many settings in order to be efficient and measurement is very slow. However, they can be effectives on large object: from 0.5 m^3 to 115 m^3.

4.2 Passive Systems without Contact

Usually used for graphical design, these systems are passive without contact since they capture information with photographic systems or stereoscopic systems. The acquisition tools are cameras and movie cameras.

Photographic systems allow building rapidly 3D models thanks to high definition numerical photos. The process associated is:
1. detecting common points between photography's,
2. automatic distance calculations and 3D wireframe design,
3. textures application using photography definition,
4. automatic virtual camera or virtual video camera positioning.

But it is necessary to precise that model precision depends on the cameras definition: more the cameras are accurate, more the model will be accurate.

4.3 Active Systems without Contact

Active systems without contact are technologies that generate short waves for measuring; for example: the laser. According to the object size to be digitized, there are various solutions:

- "desktop" laser scan: box containing the scanner. accuracy = 0.1 mm. It is suitable for only small size objects,
- TMM laser radar. High speed, high accuracy,
- 3D scanner laser. For example from Minolta. They are the most popular and are used for medicine, industrial engineering, archaeology...
- X-ray tomographic systems,
- Interferometer with optic fibber,
- Optic measure system...

4.4 Classification

The technology that will be used depends on the dimensions to be acquired (...< $1m^3$ <...< $10m^3$ <...< $60m^3$ <...), on the desired accuracy, the acquisition time available and the possibility to handle/move the object. Consequently, dealing with digitalization of patrimonial object, it will be advisable to combine the technologies (active/passive systems with/without contact) for optimizing the acquisition chain (example: without contact due to major degradation state).

Moreover, our classification takes into account the numbers of handling that have to be done in order to get the whole 3D model. Indeed, if only one point of view is considered, it will return only a stereographic view. Consequently, it is necessary to combine various points of view and/or various kinds of scanners. For instance, during the conference Computer Aided-Design-Manufacturing & Measurement Integration, Boeing presented a multiple-scanner digitalization system that is used for controlling the wings dimensions (Boeing 2001).

In order to use it within its context, i.e, taking into consideration the object conditions and what can be done or not with the patrimonial object, we establish a decision tree (figure 2). Based on criteria, it helps to find the better solution for digitalizing the object within the time available, the precision needed...

They are two kinds of criteria:

- The **operability factors** that result from the technology to be used,
- And the **data related to the object** state.

The main factors related to the operability possibilities are:

- **Measure relevance**: firstly, it is necessary to clarify if it is necessary to digitalise the whole object. For example, in case of a crane, it will be a waste of time to capture all the girders as they are identical,
- **The object being / the object full-scale**: if the object is incomplete or does not exist, missing parts will be designed according to the designer's knowledge, the external knowledge and know-how,
- **Palpation possibility** on the object,
- **Relocating possibility** of the object,
- **Radiation exposure possibility**: technologies used various wavelengths (infra-red, visible, X-ray...); sometimes, due to its degradation state, the object could not support specific wavelengths.

The initial data issued from the object characteristics can be:

- The **object material**,
- **Accessibility**: sometimes, measures have to be done from points of view that are not accessible or even inside the object,
- The **size of the object** and the volume that has to be digitalized,
- **Kinematics** digitalisation: willingness to capture the working state,
- **Digitalisation time**: when many points have to be captured, some methods have to be prohibited,
- The **accuracy**: it interacts directly with the digitalisation time and the finiality(ies) of the digitalisation,
- **Handicraft or industrial object**: an object issued from the domestic system needs more points to be defined, as all parts are not similar.

For example, linking various factors like digitalization time, size, handicraftly... if we would like to digitalize a chair, it is necessary to wonder about the relevance to capture the entire geometric definition of the chair? Only remarkable points have to be considered: then, lines can be drawn between those points and next surfaces and volumes can be designed. The following figure 2 sums up tools explained previously and the way to choose the optimum technology. All digitalization tools explained or developed previously are not mentioned but the main solutions are proposed. The circles are questions that must be asked; the arrow is green if the answer is Yes and red if the answer is No. However, please note that the method found by the decision tree may not be the only one but it is probably the best one to use. If another strategy is chosen, it will result in loosing cost, accuracy, efficiency or acquisition speed.

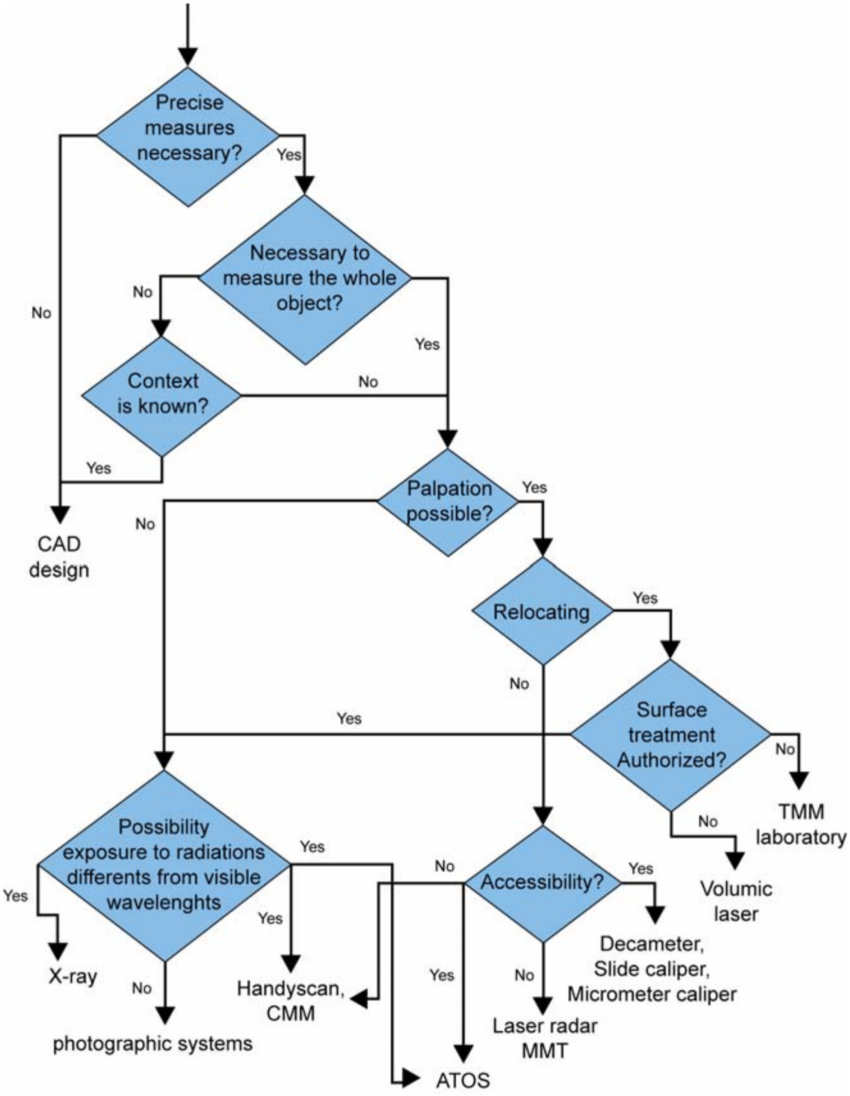

Fig. 2: The decision tree for choosing the best digitalization practice

5 Examples

In this part, two experienced examples are presented. They have been developed by our research team and our collaborators:

- Musée des Marais Salants de Batz-sur-Mer, Salt Museum, France
- Musée de l'Imprimerie de Nantes, Printing Machine Museum, France
- Morel Mapping Workshop, Architecture Digitalisation Enterprise, France
- IUT Carquefou, Mechanical Technician School, France

5.1 3D Digitalisation for Scholar Learning

This project has been developed with an educational partnership: studying an old technical object allows obtaining new technical culture. This pedagogical interest can also be associated to a second objective: learning how to use CAD tools. The projects are realised by group of 3 or 4 students. Their mission consists in producing functional digital mock-ups of old printing machines. As those machines still exist and are fully operating, students can better understand how they work but only with an external overview (Laroche and Le Loch 2005).

Indeed, old machines are very complex as they usually use one mechanical input for multiple outputs. Nowadays, for creating one movement, we generally use one motor; control is achieved by automatism, electronic or computerized; if multiple outputs are needed, we use as many motors as necessary. In the past, it was different. The main input power is furnished by human force or by a steam engine; ordinarily, the movement produced is a rotation. Next, they are many mechanisms that are totally desynchronised in order to achieve the different necessary outputs: coupling rods, wheel rods, and many adjustments. The machines are very complicated and need to be studied in details for understanding the global operation.

The project presented in this example is a printing machine built by Henry Voirin. It was put into service in 1890 and finished its use life in 1985. The press was employed for printing posters for the French company NAZE. The technology is called cylinder stopping machine. This typographical press uses surround characters coating with a small layer of ink.

The press is semi-automatic as a steam engine and later an electrical motor is used for producing a uniform rotating movement. But two operators are also required for aligning and taking off the sheets. The CAD model is made of approximately 615 components and more than 50 connections. Figure 4 presents the kinematics sketch that first has to be done in order to get a better understanding of the operation. During their work, students have faced a problem with an actuating cam. Located at the beginning of the kinematics chain, this component is fundamental for succeeding in the simulation process. Although they were authorized to disassemble some elements, the cam was impossible to get out. Moreover, this component owns a special edge and classical measurement tools were inefficient. 3D digitalization tool was then the solution that has been adopted.

Operability factors:

- **Measure relevance**: capital
- **The object full-scale**: yes
- **Palpation possibility**: yes
- **Relocating possibility**: no
- **Radiation exposure possibility**: all kind of wavelengths.

Data object:

- **Object material**: steel, lubricated and with major reflection but spray can be applied
- **Accessibility**: rather difficult as the component is inside the machine, the digitalisation system has to be small and easily handled
- **Size of the object**: less than 1 m^3
- **Kinematics** digitalisation: no
- **Digitalisation time**: limited and has to be done as quickly as possible as the student project was nearly finished
- **Accuracy**: only the edge of the component is required
- **Handicraft or industrial object**: industrial

Fig. 3: From physical object to CAD model via cloud of points

Consequently, in order to satisfy all the requirements, a new technology has been tested: the Handyscan from the Company Creaform (Creaform 2006). Based on a Canadian patent, this tool allows digitalizing an object for obtaining a cloud of points. The scanner is self-positioning in 3D space thanks to reflecting targets. It is possible to scan many times the same point for optimizing its position. The accuracy is about 3/10 mm but it is mainly depending on the object volume that has to be digitalized. This technique is without contact and cannot destroy the object, as the laser emitted is visible by human.

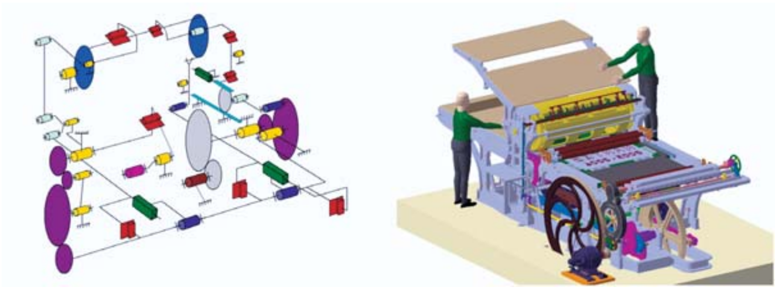

Fig. 4: Kinematics sketch and CAD mock-up of the Voirin printing press

5.2 3D Digitalisation for Heritage Conservation

In order to validate our decision tree, we have done another experience with a salt washing machine built in wood and so in a bad state. Firstly, architectural drawings have been done by curators. They produced a statement of the object at a determined date. Later, in order to have a more precise artwork, it has been decided to digitalize the washing machine and its close industrial building. It was carried out thanks to a Leica scanner: laser Cyrax 2500. Once the cloud of points obtained, it was designed with a CAD software (550 handicraft components).

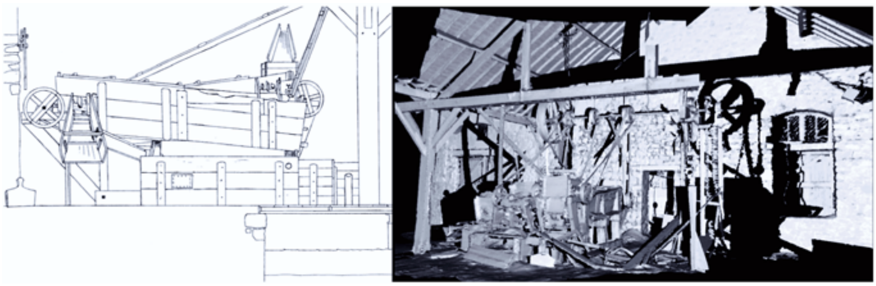

Fig. 5: Architectural drawings and cloud of points

6 Conclusion

In this communication, we are giving details of our research subject dealing with the conservation of the scientific and technical heritage. Focusing upon old objects such as industrial machines, our proposal is to virtualize them for a better communication of its knowledge. At the beginning of the process, knowledge capitalization is necessary: the context and obviously the artefact itself. In order to respect patrimony, 3D scanning technologies have to be selected and handled carefully. The decision tree can help to choose the optimum solution for digitalizing the object thanks to a good identification of the operability factors and the object characteristics. Moreover, performance and diversity technologies are being developed everyday and, may be, one day, an innovative solution will be found being fully adapted for any kind of object: decametres, callipers… will disappear?

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Using a Modified Failure Modes and Effects Analysis within the Structured Design Recovery Framework

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Abstract

A structured design recovery framework has been designed to meet the challenges associated with creating a robust engineering model for mechanical components. To assist with the testing and verification phase of the design recovery process, a matrix based modified failure modes and effects analysis (FMEA) has been developed, which targets tolerance variations, in order to diagnose potential problems. The information within the design recovery framework is extracted for the modified FMEA analysis. From the FMEA results, testing strategies are suggested based on the component characteristics. An example illustrates the modified FMEA methodology and highlights its merits.

Keywords

Reverse Engineering, Product Analysis, Failure Modes

1 Introduction to the Design Recovery Framework

Reverse engineering techniques must be applied to construct an appropriate characterisation of the product when there is no existing documentation for a component, or that documentation is no longer relevant. This may be challenging as it may require engineers in different disciplines to capture all of the ideas related to the components and their interrelationships within a given system. At the present time, reverse engineering tasks typically focus on determining the general functions for a product and its subcomponents, or creating surfaces from point cloud data that represent the form of the object being reverse engineered. Effective design recovery consists of merging both function and form elements and refining them. Each specific design parameter has an associated functional requirement. The form-function links need to be established at different levels of granularity, in context with the product architecture and operating environment, in order to infer the designer's intent and to produce pertinent product documentation. Mechanical components are designed to satisfy a specific need for a given set of constraints, and the form, functions, material and the original manufacturing processes are all interrelated. Consequently, when reverse engineering an engineered component there must be a methodology for recognizing the design intent for the individual features, and the component structure in both the physical (form) and logical (functional requirement) domains.

A systematic approach has been utilized to develop a design recovery framework to assist in the complete design recovery process. The resulting design recovery framework is an adaptation of the Zachman framework [1], which is used in Enterprise Architecture development. This framework provides a multi-level roadmap to allow the functional, structural and data information related to mechanical components to be accumulated at different levels of resolution. Concise design information is captured at the systems, embodiment and detail levels for the base component and each feature. The key perspectives and classifications that are applicable for the design recovery process at the component and feature levels are shown in Figure 1. A detailed description of the design recovery methodology is described in Urbanic et al [2] and Urbanic and ElMaraghy [3].

2 Testing and Validation

Testing and verification is a critical phase in forward engineering, and is no less so for reverse engineered parts. The reconstructed model's material, dimensions, tolerances and specifications provide information for the manufacturing domain. A testing and verification methodology needs to be developed to determine what needs to be tested and how. Potential design variations and flaws, which could lead to a loss of functionality or failure, must be detected. A failure analysis is initially performed. From these results, testing and verification strategies are recommended.

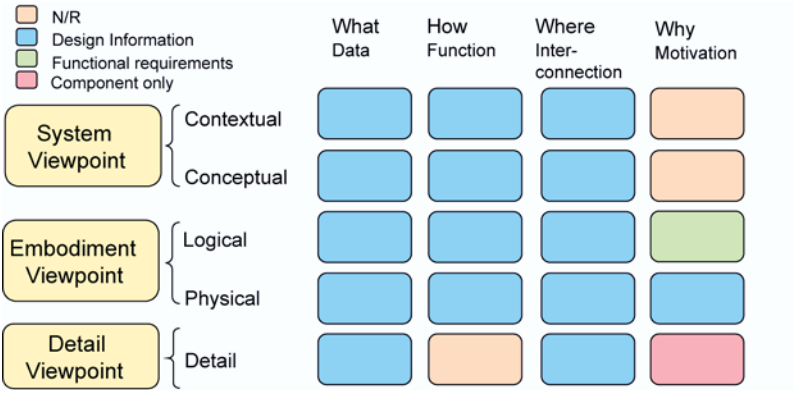

Fig. 1: Design Recovery Framework for Reverse Engineering (Component and Feature Levels), adapted from Zachman [2]

The verification process presented in this research utilizes the information contained in the design recovery framework, and flows from the logical domain, to the virtual and physical domains, and may involve multiple steps in each. A damaged power steering pump pulley is used to illustrate the technique. It has been reverse engineered by using the design recovery methodology (Figure 2).

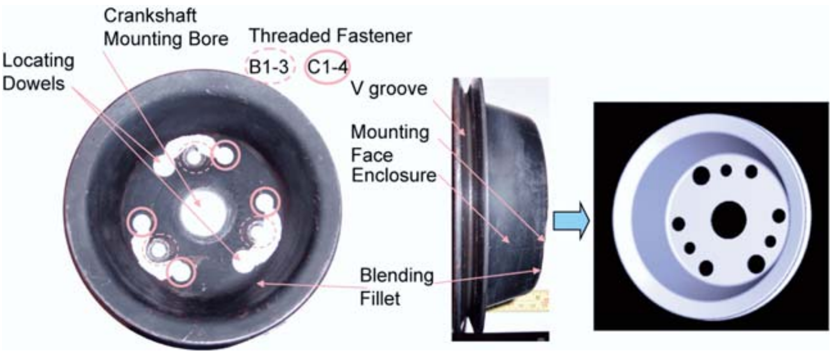

Fig. 2: Power Steering Pump Pulley and Reverse Engineered Model

2.1 FMEA

There are several methods to determine potential failure modes such as the Failure Modes and Effects Analysis (FMEA) and the Fault Tree analysis. The FMEA is one of the formal techniques used in the product development process to analyze potential product failure, either due to the product design (design FMEA), or due to the chosen manufacturing processes (process FMEA). The purpose of an FMEA is to detect and address weaknesses in the product design. An FMEA is typically developed by a cross functional team in a spreadsheet format. The team analyses the product/component to determine potential modes, and a severity rating is assigned for each failure mode. The potential causes and effects are then assessed. An occurrence rating is assigned to each potential cause and a detection rating assigned to each unique effect. The ratings are scaled from 1 – 10, with 10 being the most extreme. A risk priority number (RPN) is generated by multiplying the three factors, and the failure modes with the high RPN are selected for product or process design review (Table 1).

Tab. 1: Standard FMEA table

Item	**Potential Failure Mode**	**Potential Failure Effect**	**S**	**Class**	**Potential Failure Causes**	**O**	**Current Process Control Prevention**	**Current Process Control Detection**	**D**	**PRN**	**Re-commended Action**	**Actions taken**
			7			8			9	504		

S – severity, O – occurrence, D – detect,
RPN – risk priority number = S*O*D

The Function-failure methodology by Arunajadai et al [4] and Stone et al [5] enhances the FMEA procedure by implementing an extended standard vocabulary for the description of functions and the failure modes of components. A formal procedure is applied to identify primary and secondary identifiers to aid in selecting the appropriate failure mode and composite function-failure matrix is used to assist with the analysis. This approach complements the function-form analysis utilized in the design recovery framework; however, this work focuses primarily on failure due to wear or deformation and there is no concise means to visualize the results. In general the FMEA process is labour intensive, there are problems with consistency and duplication, or the information is too vague to be able to effectively assess the potential failure modes, effects, and causes [4-7]. Automating the FMEA process from a knowledge base may deal with some issues; however, information sufficiency is one issue that may not be addressed if a failure is caused by multiple sources of variation of the design parameters. In addition, improvements can be made to the interpretation of the results. These results should provide guidance for the subsequent testing procedures. A different approach needs to be undertaken in order to leverage the positive aspects of the FMEA.

From a ‘big picture’ point of view, the generic failure effect is failure to perform the function and the generic cause is variation in the design variables. The explicit failure modes need to be determined. The generic failure modes are:

1. Absence of a feature (process dependent);
2. Improper design parameter selection (design dependent);
3. Geometry variations leading to improper size or physical geometric characteristics (design and process dependent);
4. Improper surface characteristics, which includes smoothness, heat and surface treatments (design and process dependent); and
5. Improper material selection, material composition or structure (design and process dependent).

2.2 Modified FMEA

For design recovery, the relevant issues can be overcome by performing a modified version of the FMEA. At the design level, there are three main failure modes: improper design parameter selection, improper allowable tolerance variations and improper material selection. When reverse engineering, the key failure mode focuses on the geometric variations. The design parameters and the material properties should be reconstructed with confidence when analysing the component at the different levels of resolution; however, the procedure described here can be extended to encompass design and material failure modes. This modified version focuses on the assessing the potential failure modes simultaneously in a systematic manner and then graphing the results in order to provide insight into potential subsequent testing in the virtual and physical domains. The essential information for the FMEA analysis should be contained within the design recovery framework, as the critical design parameters and tolerances are assigned based on: (1) understanding the component and feature functions; (2) the feature interrelationships within the component and the product architecture; and (3) the potential manufacturing processes. Variations may be coupled; therefore, a potential failure may be due to a cumulative effect.

Tab. 2: Failure Modes Analysis Matrix

Size		**Depth**		**Form (1 of 4)**				**Orientation**			**Location**			**Profile**		**Surface**				
Size +	Size -	Depth +	Depth -	Roundness	Cylindricity	Straightness	Fatness	Perpendicularity	Parallelism	Angularity	Position	Concentricity	Symmetry	Linear	Surface	Thread form	Finish	Characteristics	No. of Factors	Sum

Tab. 3: Feature Description Types

Features
1 – Clearance features
2 – Complex features
3 – Enclosing or container features (cover, o-ring groove, …)
4 – External protrusion (boss, cooling fin, tab, …)
5 – Fastening features (threads, rivets, …)
6 – Free form feature (aesthetic features, contours, 3D fillets, …)
7 – Locating features (dowels, tongue and groove ..)
8 – Planar faces (mounting faces)
9 – Precision feature (shaft / hole)
10 – Precision / complex feature (multiple step bore, gear teeth)
11 – Seating features
12 – Support features

The geometric sources of variation, which consist of the geometric dimensioning and tolerancing (GD and T) callouts, the size, depth and surface characteristics, are considered simultaneously for each feature in order to address this issue (Table 2). Ancillary descriptions such as aligned, centred and so forth could also be included. Each feature being assessed is associated with a feature type (Table 3), which is leveraged when performing the design recovery tasks. For example, certain types such as a 'precision complex feature', may link into a table of standard design parameters, which provides insight into the critical attributes (i.e. gear teeth design parameters and associated tolerances) and their influence on the feature. Each relevant attribute for every feature being assessed is assigned a rating value that correlates to the derived tolerances (Table 4). These rating values are summed. The number of attributes is considered as well, as additional potential manufacturing challenges are associated with more attributes.

Tab. 4: Standardized Failure Mode Ratings

Factor Value	Description
Blank	Do not need to consider
1	Very weak (low precision, general tolerance)
3	Weak (loose tolerance)
5	Moderate (moderate tolerance)
7	Strong (tight tolerance)
9	Very strong (high precision)

For the pulley features being assessed, three are presented here (Table 5).

Tab. 5: Recovered Features

Feature Name	Feature Label	Description	Standards Table
V groove	A	Power transmission	SAE Standard V groove
Mounting holes	B	Clearance	N/A
Locating hole	C	Location	N/A

The V groove (Feature A) is a power transmission feature, and it has specific geometry and allowable tolerance variations as defined in the Society of Automotive Engineers (SAE) standards table [9]. Several critical attributes need to be considered for this feature. The mounting holes (Feature B) are clearance holes; consequently, they have looser tolerances and fewer attributes to be considered. The locating hole (Feature C) has similar geometric attributes to the mounting holes, but has moderately tighter tolerances.

Selected feature relationship information is presented in Table 6. All the GD and T descriptors and ancillary position and fit relationship data used for the modified FMEA analysis is presented in Table 7. Factors are assigned to the relevant attributes, enumerated and summed.

Tab. 6: Selected GD and T and Ancillary Callouts

	Feature	**Primary Datum**	**Secondary Datum**	**Tertiary Datum**	**Tolerance Value**	**Comment**
Concentricity	Locating hole	-A-	-B-	-C-	0.150	Centre hole
Angularity	Mounting holes	-A-	-B-	-C-	0.375	To ensure mating geometry
Angularity	Groove	-A-	-B-	-C-	0.100	0.050 per side of groove
Radial	Mounting holes	-A-				120° apart

Tab. 7: Modified FMEA Analysis

Label	**Size +**	**Size -**	**Depth +**	**Depth -**	**Roundness**	**Cylindricity**	**Straightness**	**Flatness**	**Perpendicularity**	**Parallelism**	**Angularity**	**Position**	**Concentricity**	**Symmetry**	**Circular run out**	**Total run out**	**Linear profile**	**Surface profile**
A	7	7	3	5							7					7		
B	1	1										5						
C	5	5									5							

Label	**Aligned**	**Along**	**Axial**	**Radial**	**Centred**	**Collinear**	**Coplanar**	**Mirror**	**Offset**	**Thread form**	**Finish**	**No. of Factors**	**SUM**
A											5	7	41
B				3	3							5	13.0
C		5		5								5	25.0

The results are plotted in the Failure Mode chart, and the subsequent testing and validation procedures are determined based on the levels and zones in which the features within the component fall (Table 8). The results for all the pulley features are shown in Figure 4 – the features selected for analysis in this paper are circled. For features that lie in the ‘over constrained’ regions and region A, the designer should look at the number of attributes used to determine the precision factor to verify that there are an appropriate number of attributes with respect to the rating factors. For features in the other regions, a cumulative approach is taken. First, a tolerance stack up is performed to ensure that the assembly operations can be performed with confidence (region B). For features that lie in region C, use of virtual tools such as finite element modelling (FEM) and kinematics analysis are recommended, after a tolerance stack up has been performed. These tools can provide perspective into the part’s response to different test conditions. Multiple scenarios can be readily scripted using these simulation tools. Information with respect to the material characteristics, boundary conditions, load characteristics, joint and spatial relationships, and constraints should be contained within the design framework matrices.

Tab. 8: Chart Regions

Region	Testing and Verification
A	Review form-function relationships to ensure loose tolerances and minimal information is appropriate
B	Review tolerances and perform a detailed tolerance stack up
B1	Higher level of precision required – review potential finishing processes as well as near net shape processes
B2	Lower level of precision required – review processes that generate a near net shape, review attribute factors to ensure that the no. is appropriate
C	Perform virtual simulation: such as finite element modelling, kinematic analysis, mould flow analysis (structural defects), and so forth.
C1	Higher level of precision required – review potential finishing processes, and process related simulations, benchmark competitive processes; consider a physical prototype
C2	Relatively lower level of precision required – review potential finishing processes, process related simulations; benchmark competitive processes
D	Construct a physical prototype or prototype sets for physical testing: assess relevant prototype manufacturing processes

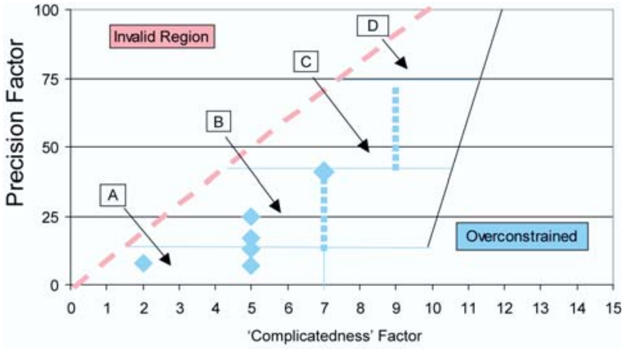

Fig. 4: Charting the FMEA Results

Competitive benchmarking of process alternatives should be considered for high precision features, and process related simulations might be required to supplement the product simulations. For features that lie in region D, a physical prototype is recommended for physical testing after all other virtual testing has been performed. The nature of an applicable physical prototype depends on the functions, materials and tolerances. Understanding the context of the application assists with decision to fabricate a physical prototype. Rapid prototyping technologies can be used to easily create a physical model; however, there are limited materials that can be utilized, and RP processes have limited accuracy [8]. If a rapid prototyping is not appropriate, traditional technologies must be used.

For the pulley case study, the majority of features have loose tolerances and minimal geometric associations, which is appropriate for clearance features. Some features have higher tolerances, indicating a tolerance stack up should be performed, which has been done. Tool path simulations have been done to optimize the groove tool selection and cutting parameters. Fabricating a prototype is inappropriate for this example.

3 Summary

For effective design recovery of an engineered component, the functional requirements for the component and its features must be linked to the relevant design parameters at different levels of resolution. Information from several perspectives and sources must be merged in order to extract the relevant data. Consequently, a structured, modular framework was developed to link the functional requirements to the design parameters in order to improve the design reconstruction process. To assist with the testing and verification stages of the design recovery process, a modified FMEA procedure that focuses on failure modes is introduced to diagnose form variations of the recovered design, and to provide insight into suitable supplementary testing and verification procedures. The design recovery framework contains the design concepts, variables and structural relationships that can be used as the basis for an FMEA. However, the traditional approach for an FMEA is time consuming, does not consider multiple sources of variation in an intuitive manner, and does not directly provide any insight as to the next stages of the testing and verification process without the designer(s) performing extensive analysis. A streamlined methodology that focuses on form and surface variations has been developed that quickly highlights the characteristics of the features graphically. Testing and verification strategies are proposed after all the features are analysed, based on the location of the precision and complicatedness factors within the FMEA graph. This methodology is illustrated using a reverse engineered power steering pump pulley.

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Knowledge Reengineering for Reverse Engineering Purposes

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Abstract
Often in the case of a machine defect, the easy and quick production of necessary spare parts becomes impossible because of lacking documentation. In such cases, Reverse Engineering techniques are used for the reconstruction of damaged or worn mechanical parts. The paper points out how to obtain additional knowledge in the case when geometric data is not sufficient for the reverse engineering of mechanical parts. The paper presents a method and a case study of additional knowledge reengineering for worn machine parts regeneration. The method was used for gathering additional knowledge essential for the regeneration of a hydraulic bending machine.

Keywords
Knowledge reengineering, CAD, Reverse Engineering

1 Introduction

The need for the reengineering of construction knowledge necessary for the reconstruction of physical objects exists in a number of areas This is due to the fact that the original sources of such knowledge are, for various reasons, unavailable. They may have been lost, destroyed or have become outdated. In the case where the construction documentation does not exist Reverse Engineering techniques are used by engineers to reconstruct machine parts.

However, the majority of reconstruction methods are based only on the geometrical shape of the reconstructed objects. In the case of damaged objects knowing the shape of the objects is not enough for the reconstruction of a fully functional copy. In such cases it is necessary to draw conclusions about the intentions of the constructor of the original model and its original shape as well as functions of the reconstructed object by finding additional sources of knowledge about the object. This article presents the problem of the reengineering of the knowledge necessary for the reconstruction of a damaged hydraulic bending machine.

2 Knowledge Reengineering

The authors have suggested a reconstruction method based on not only the shape of the reconstructed object, but also on the knowledge which can be gathered from the surroundings of the object. All the parts and subassemblies with which a given object mates and makes kinematic pairs in the mechanism are called the surroundings of the object. This approach enables the reconstruction not only of the geometry, but also of other features and functions of a given object. Additionally, it enables the recreation of data, based on which, complete documentation for the reconstructed object can be created. The algorithm of knowledge reengineering has been presented in figure 1 below.

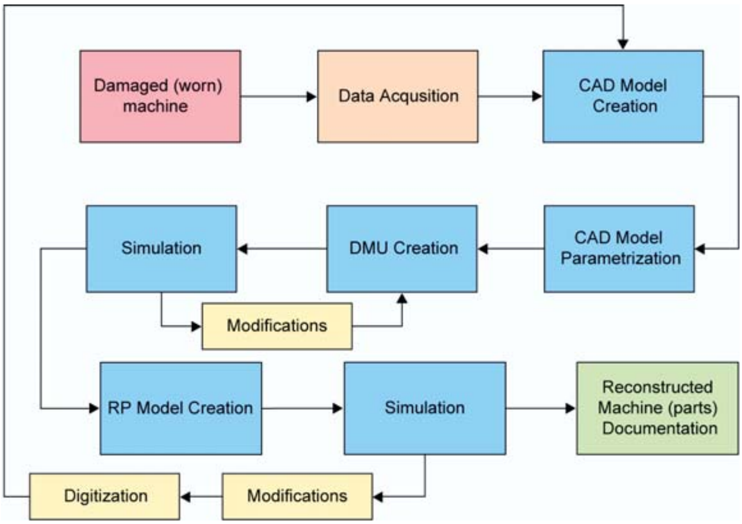

Fig. 1: The algorithm of knowledge reengineering

The first stage involves gathering all the necessary knowledge for making a CAD-3D model. Applying the holistic approach to the mechanism, it is possible to reengineer construction knowledge about its parts. This knowledge can be obtained from different sources. Apart from the knowledge of the geometrical shape of the object obtained through digitalisation, the knowledge necessary for the recreation of the shape and dimensions for the CAD model can be obtained from the analysis of the machine principle of operation. Here the theory of machines and mechanisms as well as construction principles can be used. Applying this theory enables the construction of the structural scheme of the mechanism in question, based on which, a kinematic model can be built. This will enable a simulation of the functioning of the mechanism, which will make it possible to draw conclusions about the initial assumptions of the constructor and about what shape certain subassemblies should have to perform certain functions. Standards for fitting, clearance and tolerance for the construction of subassemblies of a certain class can also be used as the source of knowledge.

An invaluable source of informal knowledge, so far underestimated, is the knowledge which can be provided by the workers operating the machine which is being reconstructed. It can give proper direction to the search for formal knowledge and significantly shorten the time needed for knowledge reengineering which is needed for the recreation of a certain object. In small companies, workers operating the machines often take care of the maintenance. Thus, they know a lot about certain machines. By interviewing the workers, information can be obtained about any symptoms of malfunctioning or any changes in the parameters of the process performed on a certain machine. This will provide necessary guidelines as to what to pay special attention to during the reconstruction process.

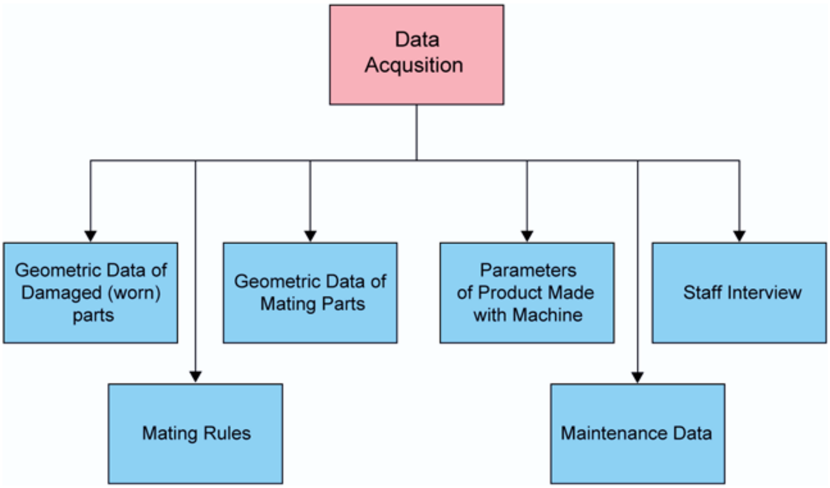

Fig. 2: The sources of knowledge about the reconstructed object

After gathering all necessary knowledge for building the CAD-3D model, modelling in CAD can be initiated. Having a parametric model at our disposal, necessary modifications can be made, such as the replenishing of insufficient material. The DMU model, which will enable the simulation of the reconstructed model mating, then needs to be built with the use of the 3D models. If the results of the simulation are unsatisfactory and the model of the mechanism is not functioning according to the initial assumptions, it is possible to make changes in the reconstructed subassemblies by changing certain parameters. The last stage involves the making of a physical model with the use of so called rapid prototyping methods. In the case of any malfunctioning of the mechanism after the simulation has been completed, two different ways of solving the problem can be adopted. If the geometry of the object has to be adjusted – bigger or smaller clearance for example – it can be achieved by changing the CAD model parameters. However, if the necessary changes involve more than just geometry handling, a modification of the physical model has to be made so that the required mating conditions are ensured. After this the digitization-modelling cycle has to be repeated.

Reconstruction of the Hydraulic Bending Machine

The object that needed reconstruction, and for which the new method was developed, was a hydraulic bending machine. The proper functioning of the machine was to be restored despite the insufficient technical and construction documentation. The main elements of the machine are: a welded body, pressure beam, lower beam, bending beam, four identical lever mechanisms responsible for the working movement of the bending beam and a hydraulic system with the cylinders propelling the lever mechanisms. Basic parameters: total bending length – 6 m, maximum thickness of the bent sheet – 1 mm – and the maximum bending angle - 135°. The general view of the machine is presented in the figure 3 below.

The goods produced with the use of the machine did not adhere to the set parameters and after operating for a certain period of time the machine needed repairing. After the repair the accuracy of the produced goods was still unsatisfactory. Due to the faulty repair an initial stress was introduced during the assembly which resulted in the faster deterioration of subassemblies.

On the horizontal axis of the diagram the length of the sheet has been shown, while the vertical axis shows the value of deviation of the required bending angle. As can be seen on the diagram all the deviations were negative and ranged from - 1° to - 14°. The distribution of deviations was similar for all the bending angles. The biggest deviation existed for 90° and the smallest for 135°. It might have been due to the fact that for the maximum angle (135°) the sheet is pressed to the pressure beam and formed on it.

To solve the above problem in machine regeneration, the following method was employed.

Fig. 3: The general view of the machine

At the very beginning of the reconstruction process in order to define the problem a trial run was made. It involved sheet bending at the angle of 45°, 90° and 135°. The results have been presented in the figure below.

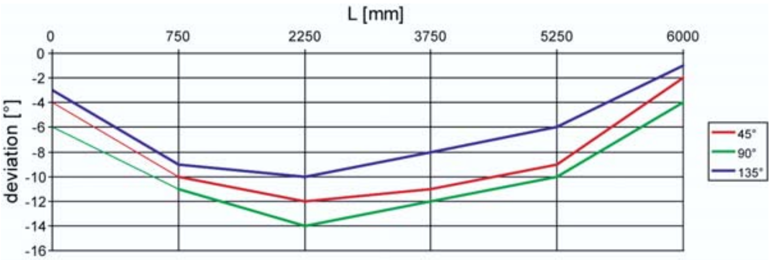

Fig. 4: Deviation diagram for the hydraulic bending machine sheet bending

After dismantling and making sketches of certain parts of the four mechanisms the reasons for the inaccuracies in the functioning of the machine had to be found. As the knowledge necessary for the reconstruction of the machine was being gathered, the following questions were formed:

- How does the lever mechanism work?
- What are the nominal dimensions of subassemblies ensuring the proper functioning of the machine?

At the stage of searching for the solution to the problem, after defining what knowledge was necessary for the reconstruction of the machine and what knowledge still needed to be gathered, the potential sources of obtaining this knowledge were listed. They have been presented in the figure below.

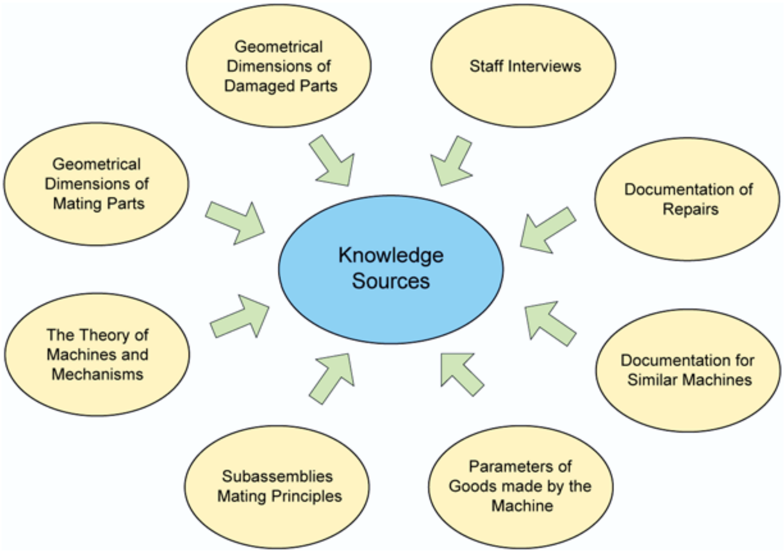

Fig. 5: Potential sources of knowledge necessary for the reconstruction of the machine

Having gathered the necessary knowledge it was possible to make an assumption that the malfunctioning of the machine was caused by flaws in its kinematic system which made the proper working movement of the bending beam impossible.

As there was no access to the machine documentation or construction documentation of a similar device, the principles of operation of the machine had to be deduced. Based on the length of different parts of the mechanism a structural scheme of the lever system was drawn. This presented in the figure below.

Based on the analysis of the mechanism operation principle it was found that the key element to the proper functioning of the machine is the axis of rotation of the bending beam. A theoretical scheme of sheet bending of a 1:1 scale was drawn in order to ascertain the required characteristics of the rotation of the bending beam. The diagram below shows a theoretical scheme of the key positions of the bending beam during sheet bending.

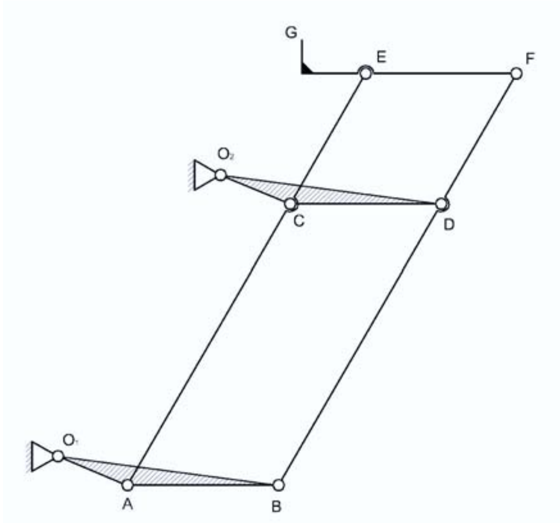

Fig. 6: The structural scheme of the hydraulic bending machine lever system in 90° service position

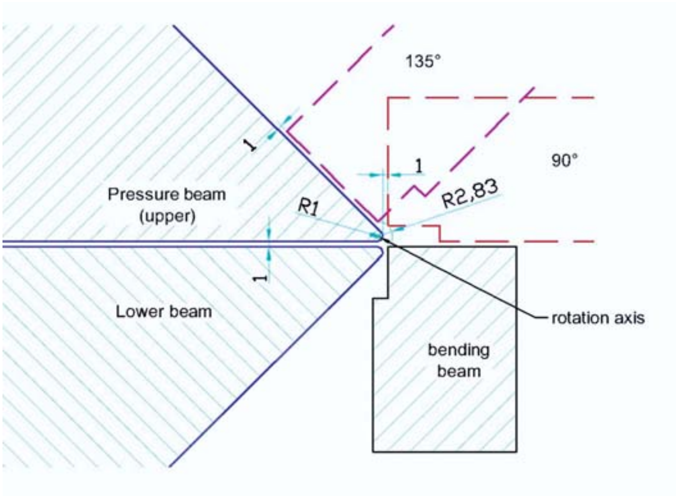

Fig. 7: The scheme of sheet bending based on the rounding radius of the edge of the pressure beam

Based on the kinematic model and the results of the measurements of the actual parts, CAD – 3D models for certain parts of the machine were made. An example of the 3D model is presented in the figure below.

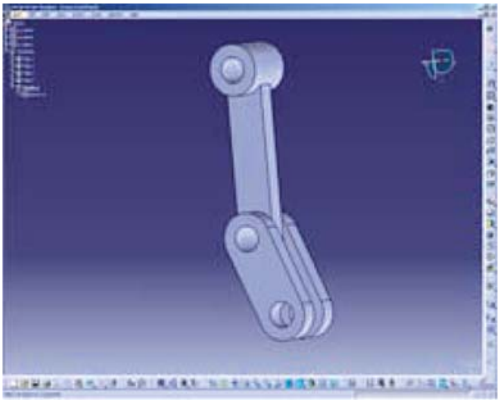

Fig. 8: CAD – 3D model of the hydraulic bending machine subassembly.

The models underwent parameterisation to enable the modification of their dimensions so that after assembly the mechanism would realize the assumed movement of the bending beam.

The next step was the making of the DMU model, as presented in figure 9, in order to verify the proper operation of the mechanism.

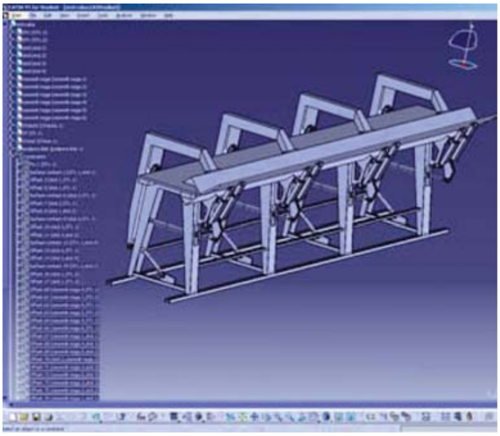

Fig. 9: DMU model of the bending machine

After completing a simulation on the DMU model and making sure that the mechanism was functioning properly, the construction documentation of the bending machine was made. Pictures of subassemblies and a picture of the whole machine were drawn. It was also necessary to design proper instrumentation for the regeneration of damaged subassemblies. Based on the CAD – 3D models of the bending machine subassemblies, the instrumentation was designed.

After the reconstruction of the machine a test run was again carried out. The results have been shown in the diagram below. For comparison the results of the test run before the machine reconstruction have also been shown.

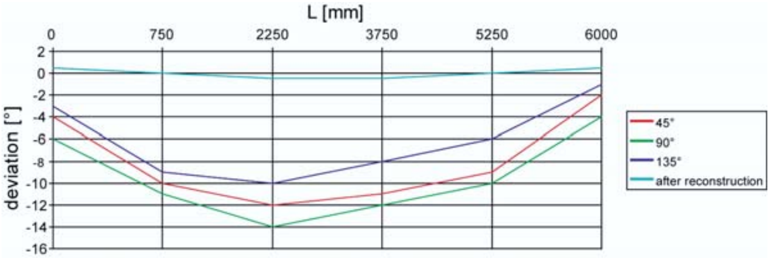

Fig. 10: Results of work carried out after reconstruction of machine

After the reconstruction the values of deviation were equal for all the angles oscillating in the range of ± 0,5°. These values were within the tolerance range of the product made by the machine.

3 Conclusions

As shown above the suggested method enables the reconstruction of the machine where machine documentation is not available. It is especially important in Poland where small companies often buy used machines without technical documentation due to limited financial resources. Such machines often require maintenance even before they are set operating.

Due to limited time, the gathering of knowledge is also limited. When the machine is used in production, its reconstruction should take as little time as possible due to the high costs incurred by stoppages. Therefore it is essential that proper sources of knowledge reengineering are located at the very beginning of the process. During the process of the reengineering of the knowledge to be used for machine reconstruction, the recreation of the principles of machine operation and the building of the kinematic model proved to be the most troublesome.

The CAD-3D models made it possible to design the instrumentation necessary for the regeneration of the worn parts of the bending machine.

If separate parts of the machine or even one of the lever systems had only been taken into consideration, the reconstruction of the whole mechanism would have been impossible. It proved to be possible only because a holistic approach was adopted and the machine was treated as a whole.

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Extended Virtual Prototyping

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Abstract
The content of this paper are the research topics at the TU Ilmenau in Virtual Engineering of micro- and nanosystems considering the spatial presentation. Further the concept of an audiovisual CAVE is presented which combines the stereoscopic projection with the new technology of acoustic wave-field-synthesis. Currently the aim of interdisciplinary research is the realistic reproduction of technical systems acoustical behaviour. In connection with this, the spatial presentation of acoustical behaviour facilitates psycho-acoustical evaluation of technical solutions during design process.

Keywords
Virtual Prototyping, Wave-Field-Synthesis, Product Optimisation

1 Introduction

Virtual Engineering enables the analysis of relevant product properties of technical systems. Complex product- and process-simulations based on parametric virtual product models realize this analysis. The results can be discussed interdisciplinary during multimodal immersive presentations.

2 Methods and Tools in Product Development

Virtual Reality (VR) is deemed to be a synonym for intuitive interaction with objects in a virtual world. Beside the pretensions on hardware and projection systems this aspects are the advantages of VR in product development. The user can immerse and move in the VR-scene as well as interact with design results represented as virtual prototypes. So VR enables a better recognisability of problems, better appraisal and feedback of design solutions with realistic shape at early phases in the development process. VR supports also the collaboration with specialists from other areas. So can be increased the quality of technical systems.

The aim of the design process is to develop a shape of a technical system to realize a specified function taking into account requirements. These requirements have to be determined in the task specification phase. An efficient way to do this is to use process simulations with tools of virtual prototyping. In this way necessary dimensions, tolerances and movements can be ascertained. Fig. 1 shows the process simulation of the surface scanning of a wafer. For this task a mechanism is needed which enables a two dimensional relative positioning between a cantilever and a wafer. The geometry of the wafer is well known. By a simple reproduction of the measurement principle on the model of the wafer in VR the mechanism requirements can be deviated. The next steps are functional structure, solution principle and preliminary 3D shape design.

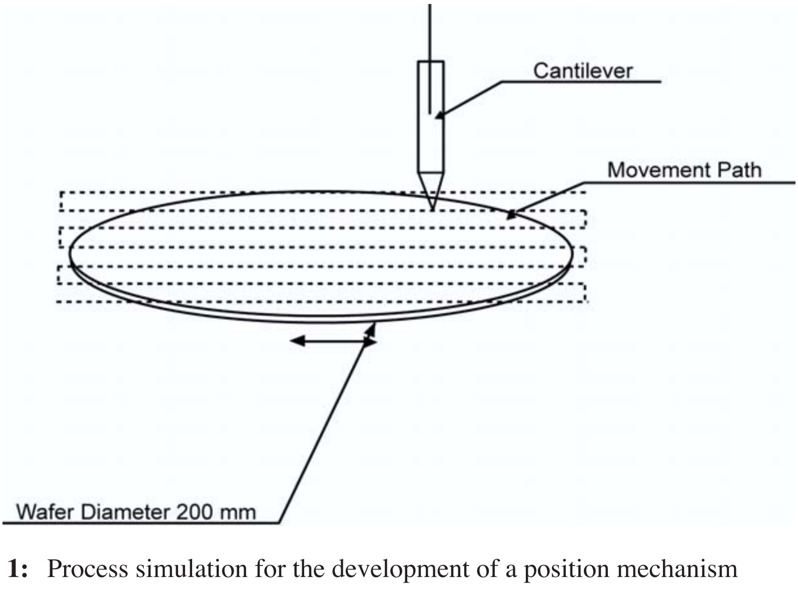

Fig. 1: Process simulation for the development of a position mechanism

The development of skimpiest micromechanical and heterogenic function units requires the handling of complex structures [3]. Because of the complexity of these systems it's difficult for seasoned persons to work without errors. An important aid is a spatial visualisation in real-time. Micromechanical research objects determine new demands. That's especially the regard of dimension- and form-tolerances as well as the inclusion of new complex simulation methods, like coupled MBS-FEM simulation. These innovative methods are used to test behaviour and design of new concepts of high-precision mechanism for nano-position and nano-measuring machines.

The new concepts for the guidance of a horizontal axis are characterized by a zero backslash frictionless and well constraint horizontal movement with a positioning accuracy of 10nm. For this several concept variants were build and analyzed with tools of virtual prototyping (Fig. 2). The system MASP (Modeling and Analysis of Solution Principles) [1] enables the designer in the early design stages to carry out design guidelines as minimum error configuration, function separation or integration, direct and short power transmission, symmetry and well constraint design. Using a VR-system developed at department of Computer Graphics at TU Ilmenau 3D solution principles could be analyzed in terms of the restrictions on the large Powerwall.

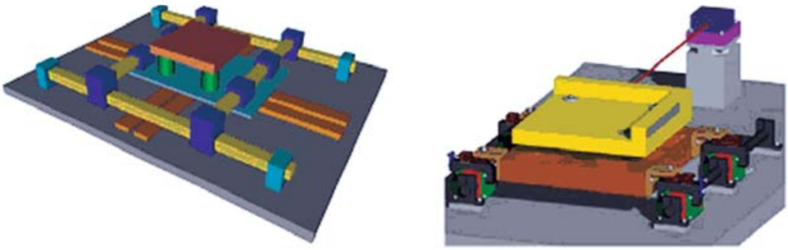

Fig. 2: Guidance concept of a horizontal axis

Virtual product development currently focuses on presentation of product properties over the visual human information channel. But the reachable optimization in VR depends on impressions, observations and reactions of involved persons. Therefore the aim is to include further sense organs. In product development this is primarily the acoustic and haptic sense.

3 Concept of an Audiovisual CAVE

The demands on product development and the limits of visual perception require the inclusion of acoustic behaviour of technical systems and their psycho-acoustical evaluation in design processes. Also the combination of realistic visual and acoustical impressions increases the immersion. So the user can concentrate on the relevant task.

Fig. 3: Audiovisual CAVE-System at competence centre Virtual Reality

Currently a system for creating a realistic acoustic sound impression is build at competence centre "Virtual Reality" at TU Ilmenau (Fig. 3). This is a flexible 3-side-CAVE with the combination of stereoscopic projection and wave-field-synthesis (wfs). Wave-field-synthesis is an acoustical reproduction concept for realistic sound fields in any virtual environments based on Huygens Principle. This new technology enables a realistic sound impression independent from listener position. This controllable and spatial playback of sound sources (gears, engines, bearings etc.) is a capable tool for machine acoustics analysis and sound design. The user can manipulate the VR-scene interactive because the wave-field-synthesis algorithm renders in real-time.

The condition for the reproduction of the sound field is a closed circle of loudspeakers around the listener area (Fig. 4). Based on the Kirchhoff-Helmholtz integral of wave theory the sound field can be calculated [4]. The loudspeakers have a defined distance calculated by the signal theory. The distance determines the Aliasing Frequency which is the highest exact renderable frequency. Virtual sound sources can be placed as point sources behind the loudspeakers or as focused sources in front of them. Room acoustic properties can be reproduced with plane waves [4]. Currently is studied how wave-field-synthesis can be used for machine acoustics simulation and sound design.

The use of wave-field synthesis for psycho acoustical investigation in product development requires audio-visual models which describe the acoustical behaviour depending on shape and functional input parameters of technical systems.

An important property of these models is the complexity of the data which determinates the calculation time. To get acceptable latency times the audio-visual models are separated in a shape representation, like conventional VR-models, and a physical representation, for simulation of the acoustical behaviour. The representations are linked to exchange parameter variations.

Different methods are used for simulation of the acoustical transmission. The most accurate method is the numerical FE-Method. A more abstract but easier to calculate method is the SEA (Statistical Energy Analysis). The decision about the optimal analyze method depends on necessary accuracy and the dominate frequency band.

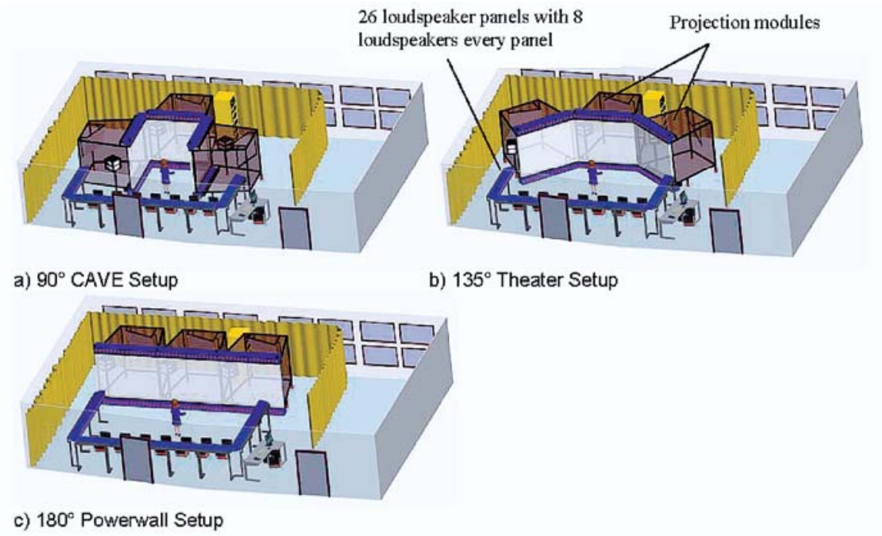

Fig. 4: Model of the flexible audiovisual CAVE

Fig. 5 shows the structure of the audio-visual model using FEM for simulation of acoustical transmission and BEM (Boundary Element Method) for sound radiation. Both methods need acoustical parameters of the structure. To reach more realistic results the structure parameters are ascertained by experiments. So hybrid physical models emerge. The parameters can be modified for sound design over user interface.

During real-time interaction the FEM und BEM calculation process is too extensive. So the simulation is done in pre-process and only the results are used during model interaction.

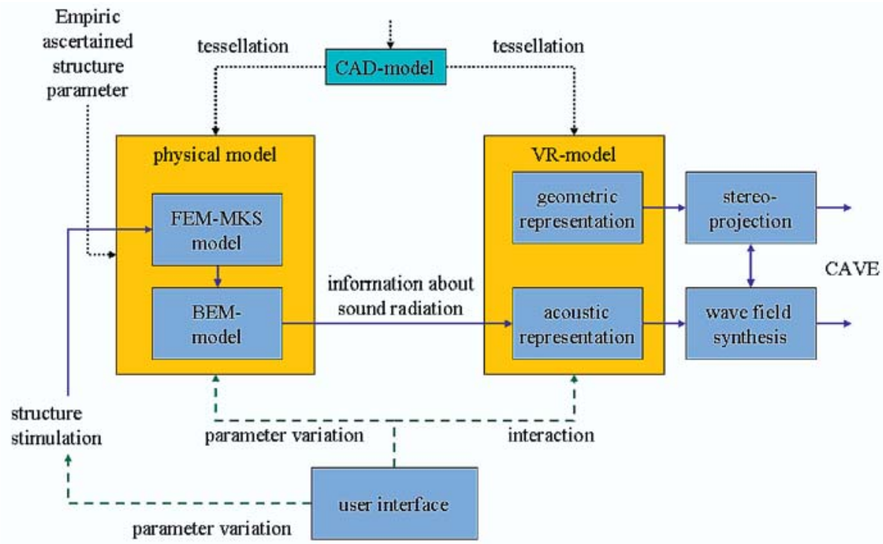

Fig. 5: Structure of the audiovisual VR-model

A very important question is the discretisation of the surface for placing wfs sound nodes. Currently wfs supports up to 32 independent sound sources with a sphere characteristic. So on the surface of the technical systems up to 32 positions have to be found, which describe the sound radiation.

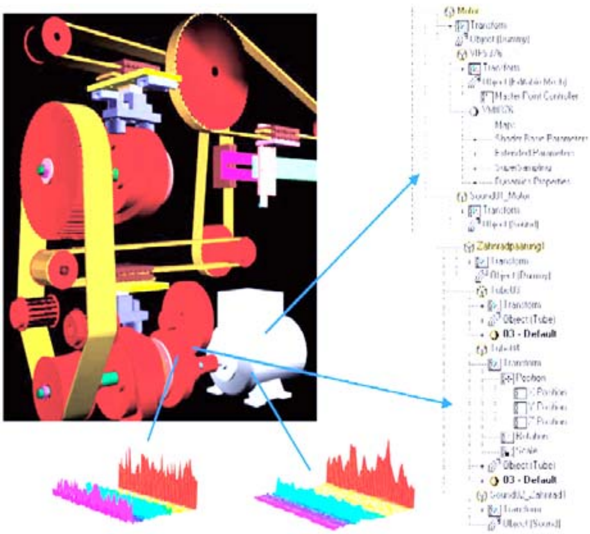

Fig. 6: Acoustical representation in scene graph of a pick & place unit

The sound sources are represented as special wfs sound nodes in the scene graph. The nodes contain parameters like position, intensity, direction and the resource locator for the audio file. These parameters are well known from VRML sound nodes. Furthermore this sound nodes contain information about plane wave characteristic, distance depend flags and wfs options, which are not comprised in standard VRML. For using an available scene graph some VRML sound parameters are interpreted new.

First models were created for assembly machines, like a pick & place unit without a complex frame (Fig. 6) and a revolving automatic assembly machine (Fig. 7). The first researches with the pick & place unit base on empiric measured sound data.

Fig. 7: VR-scene of the revolving automatic assembly machine

During a design review mostly the technical systems have to be placed close to the users. That way the sound sources are in front of the loudspeakers and have to be focused. In order to assure that all users have the same sound impression and hear the sound sources at same position the reconstruction area should be considered. The reconstruction area depends on position of the active loudspeakers and the extreme position of the users.

Fig. 8 shows the reconstruction area for a simple sound source in a rectangular loudspeaker area. For the audiovisual CAVE-System the theoretical reconstruction area is shown in Fig. 9. The real reconstruction area is smaller by reason of psycho acoustic aspects and the focus method. This area has to be considered during VR-presentation and in the VR-models.

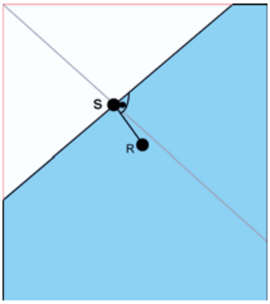

Fig. 8: Reconstruction area for a single sound source in a rectangular loudspeaker area (red are the active loudspeakers, the blue area is the reconstruction area, S is the position of the virtual sound source and R is the centre of the loudspeaker area)

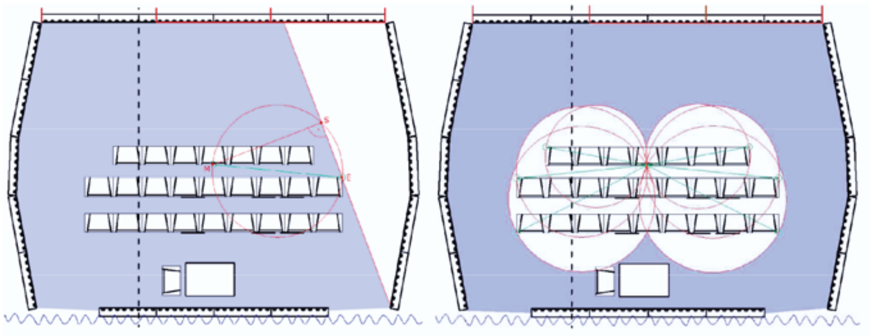

Fig. 9: Reconstruction area in the audiovisual CAVE-System

A difficulty at combination of stereoscopic projection and wave-field-synthesis is the observance of spatial localization borders. The stereoscopic picture is nearly optimum only for one tracked person. There are some spatial distortions based on the projection and viewing conditions. All other users see always a distorted image. Furthermore they see the 3D-model at another position. The reproduction of the virtual sound sources with the wfs is for a group of users exact. They hear the sound sources at same position. So accrue two different localization points for the visual and acoustic incident. This effect become troublesome above a threshold angle of 6° to 8° between user and the both incidents [2]. Using the powerwall configuration (Fig. 4) this threshold is reached quickly. Fig. 10 shows the possible position of an audiovisual object behind (red line) and in front of the powerwall (blue line) which doesn't become troublesome depending on the users position. The task of the ongoing research is to ascertain the influence during design reviews and to optimize the interconnection of stereo projection and wfs to reduce the trouble.

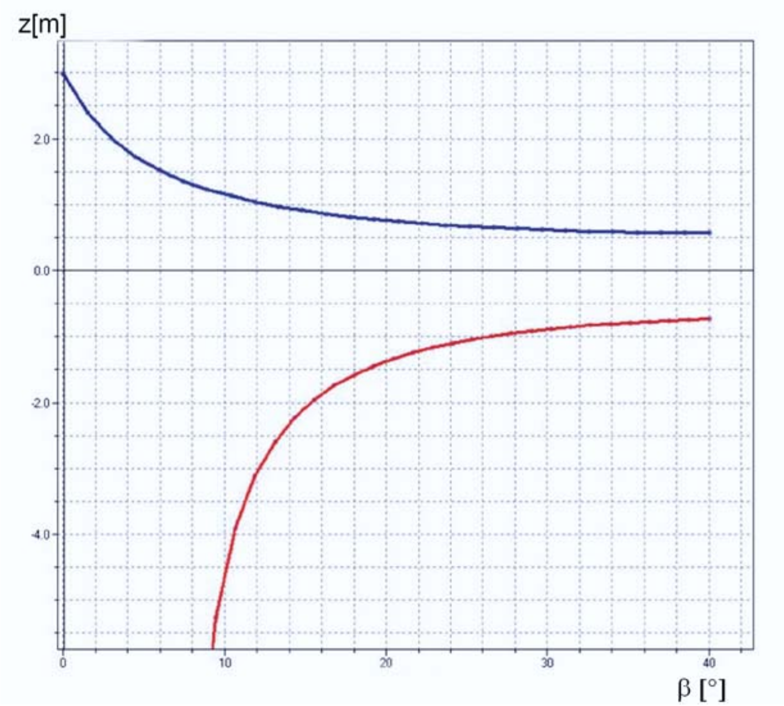

Fig. 10: Possible positions of audiovisual models on powerwall depending on user position (red line - in front of the powerwall; blue line - behind the powerwall)

4 Summary

Virtual Prototyping in connection with the use of extended Virtual Reality opens new possibilities for evaluation of technical systems in the product development. Stereoscopic projection, interaction in real-time, complemented with acoustic perception in virtual space deliver the user realistic impressions about the designed product. A research field is created by integration of the audio-channel in Virtual Prototyping for machine acoustics and sound design.

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MagicMirror & FootGlove: A New System for the Customized Shoe Try-on

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Abstract
Some times, when you have the experience in a shop to buy shoes, it happens that you cannot find your preferred model. Starting from this simple problem, a new concept of shoes shop model comes out: the customer doesn't use a pre-built set of product samples but he can digitally customize in the shop the shoes, try-on the shoes in augmented reality and then order their realization. This type of approach opens new ways to the shop concept moving from concept of mass production to the idea of mass customization. In this field ITIA is carrying on, inside the CEC-Made-Shoe Project, some research activities finalized to the support of the try-on process of customized shoes with two systems, called MagicMirror (MM) and FootGlove (FG), for the feelings of wearing shoes. In this article, last results and improvements to MM and FG prototypes are presented.

Keywords
Mass Customization, Augmented Reality, Aptic Device, Shoes

1 MM General System Process and Architecture

The MM process (Fig. 1) is the following: the user with an interactive digital Catalogue application selects the brand, the model of the shoe and customizes some elements of the model. The model is then loaded into the MM application from a 3D models database and the user does the virtual try-on. The system is composed by a wide LCD screen that acts as a mirror, a camera that live shoots the user and sends the images to the screen, a tracking system to track the position of the feet of the user with 6 degrees of freedom

(DOF) to digitally superimpose the virtual shoes to the live video. To mix in realtime the virtual shoes with the live video, a uniform background is used for chromakeying. A PC with the MM application and the Catalogue manages the software running. The MM application and the Catalogue can also run on different networked PCs. The realtime graphics module is developed with OpenGL library.

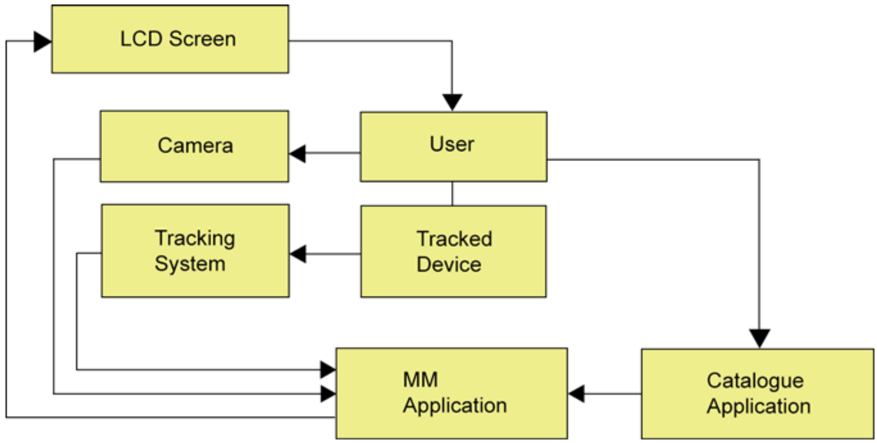

Fig. 1: General MM system architecture

2 Chromakeying Issues

The user wears special blue shoes so that the system can draw the virtual shoes only in the blue area of the whole image from camera. In this way, the virtual shoes images are correctly mixed with the video. Some problems occur when not all the blue region is filled with the virtual shoes: in this case it is needed to replace the rest of the blue with the real floor original image in the corresponding position. Due to environmental and user's shadows, this leads to local visual artifacts in luminosity and contrast. To avoid this problem, a blue carpet is used so that it is replaced with a virtual floor so that there are no such artifacts (Fig. 2). Another thing to keep into account is that the device mounted on the user's feet to track their position occludes the blue of the special shoes, thus, in the final composed image, we see the virtual shoes still with the device image. This can be avoided by removing the image of the device and replacing it with the corresponding part of the underlying virtual shoe. To obtain this, the application, before drawing the virtual shoes on the blue part of the image, draws a 3D model of the device over the original camera image and marks that region as ready for chromakeying.

Fig. 2: A blue carpet is replaced by a virtual floor to avoid artifacts

3 Experimented Tracking Methods

In the development of the MM system the main problem is the tracking of the feet: it should be precise at about 1 cm and 3° and it should be stable to avoid virtual shoes flickering that is disturbing for the user interaction. Two tracking systems have been experimented: a visual marker recognition system based on a software library called ARToolkit, and a commercial motion capture system. This last one has been the demonstrator that a correct and stable tracking can be done for implementing the MM system.

3.1 Tracking with Camera

A marker is a paper sheet square with a pattern drawn inside, that is placed on the user's foot. The marker is tracked at 6 DOF by the system through the camera. There is some tracking stability problems because on a side the camera should be properly oriented to capture an enough large scene with user's body, and on the other side this orientation makes the camera's lens not parallel to the markers, thus by degrading the quality of the visual tracking. As alternative, a camera properly oriented to track the markers, and another camera properly oriented to live shoot the scene with the user have been adopted. In this way, the camera for markers tracking has been placed on the top of the screen, with a zoom factor, pointing correctly to the markers. With two cameras the markers position should be transferred from their original camera reference system to the reference system of the camera that shoots the user. Thus, a calibration procedure is introduced at the startup of the system: both cameras attempt to track the same marker and then the reference system transformation is computed and used. Also in this second case, some problems occur: the visual tracking is unstable for lighting conditions, camera resolution and poor precision for the rotations that makes the positioning hard to manage.

3.2 Tracking with Motion Capture System (MCS)

A MCS is basically an hardware-dedicated set of cameras (at least two) capable of tracking markers (that are typically little spheres, 0.5-3 cm diameter) in the field of the infrared light. The MM with the MCS has produced very good results. A camera has been used to live shoot the scene with the user, it has been placed at the bottom of the screen. The MCS used is a Polaris Vicra of Northern Digital Inc. The markers tracked, called "tools", are small crosses with at their tips little reflective spheres. The system tracks, with 6 DOF at about 20 Hz, the tools that can be seen in its field of view. The MCS and the camera are mounted in a fixed position into the housing of the MM screen. A calibration procedure to transfer the tool position from MCS reference system to camera reference system is performed once and saved to a file. For the calibration, the visual tracking system has been used to track a static marker through the camera (in camera reference system) and the MCS to track a static tool (in its own reference system). Since both the marker and the tool must be viewed by their tracking systems, they have been mounted on a board with a precise known relative position. For the MM interaction the feet should be tracked by the MCS. For this, two "special shoes" have been built (Fig. 3): they are boards with the tool mounted on the top and covered with stockings of the chromakey blue color. The user wears the special shoes, the motion capture system tracks the tools mounted on and thus the user can do the try-on of the virtual shoes with the MM.

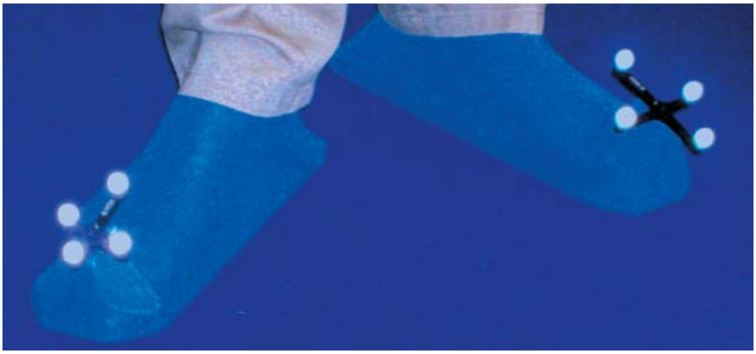

Fig. 3: The special shoes and the tools for the motion capture tracking

4 MM Conclusions

The MM is a system for the try-on of virtual shoes. The hard key point is the tracking of the user's feet in order to correctly reproduce the image of the virtual shoes into the live video of the scene. The experimented motion capture system has demonstrated that it is a good technology for a precise and stable tracking, that is the main point of the MM application.

5 FootGlove System

The 3D structure of the FG pre-prototype is meant to reproduce in approximate manner the internal volume of shoes through a finite number of element. The number and schema of those mechanical elements that interact with customer foot are the result of geometric studies and is based onto the concepts of Development Centre (DC) and last surface grading with slices. DC and slices have allowed to define a number of directions common to all lasts and the result was the identification of several intersection points with the surface of the lasts. The directions and intersection points have allowed to define kinematic groups and to convert all geometrical design concepts in to the design of the FG pre-prototype.

6 Planning

The final version of the FG will be a complete automatic system, simple to use and with dimensions a bit bigger than a shoe of size 11. To understand the meaning of the theory of geometrical grading developed in the feasibility study a manual pre-prototype has been realised. The choice of a manual pre-prototype comes from a less complexity and costs in realisation of the pre-prototype. The goal of the manual pre-prototype is the comparison between data coming from simulations and real data coming from real last to understand how to improve the pre-prototype.

The FG pre-prototype (Fig. 4) is composed by ten columns mounted on a base, built by rapid prototyping, with prismatic guides for two, three or four sliders that are able to move in the directions defined by the concepts of DC and last surface grading with slices.

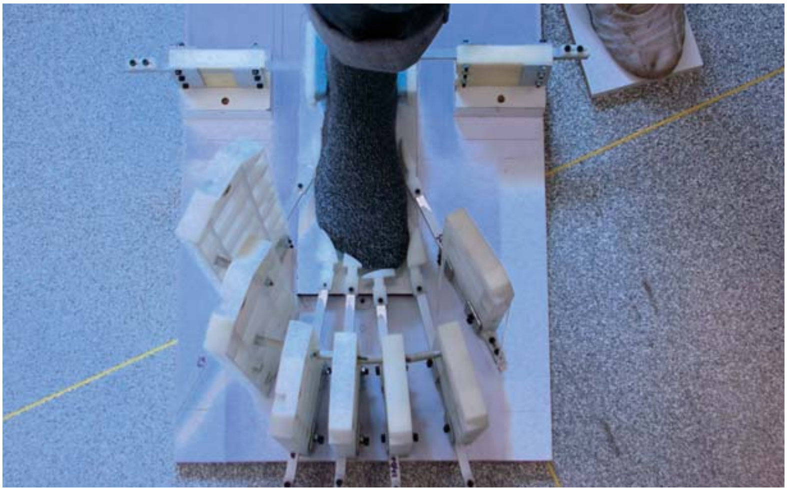

Fig. 4: The FootGlove pre-prototype

The amount of the sliders is thirty, each slider has a particular head according to the position in the column and to column's position respect the base. The seven columns mounted in front of foot have the job of simulating the contact between front upper and foot, each column is composed by an amount of sliders depending on the position of column respect the foot and surface to simulate.

The more critical point of this design activities was the definition and accomplishment of all the heads to be placed at the end of the sliders and to be in contact with the feet. It has been understood that these elements can't be standardized and have been designed one by one to completely match the requirement for a good contact surface, the direction of the slider movement and the avoidance-reduction of collision with all others elements and heads. The heads are sphere portions positioned tangent at the intersection between the virtual last and the corresponding direction of translation. The spheres are cut with planes that avoid the collision between heads during translation. The back columns are mounted on a undercarriage to facilitate introduction of foot in the pre-prototype, they have the rule to define the length of the shoe and the width of shoe in the ankle and heel zone.

7 Kinematic Simulation of the FootGlove pre-Prototype

To be able to utilize the system, the value of configuration parameters must be evaluated. To solve this task a 3D kinematic simulation model of the FG pre-prototype has been made with IGRIP to define and simulate the methodology for placing the lasts into the FG pre-prototype and to estimate the value of stroke for every slider and every last.

Shoes and lasts maker have recently introduced the use of 3D CAD systems to support both the design of lasts and shoes. Within the European Project CEC-Made-Shoe there are many shoe factories that utilize 3D CADs but they apply their traditional methodology and knowledge to the design phase of shoes and some differences are emerged during the studies of last shapes and 3D CAD models. Most relevant ones were the differences in definition of main coordinate system that didn't make possible the direct use of last 3D model into the simulation environment with the virtual FG pre-prototype. To be able to use all last's 3D models a methodology to normalize the position of the virtual last has been defined. The method consists in determining with high accuracy the position of the DC relatively to the bounding box (BB) of the last insole. With the definition of a methodology that enables to detect position of DC in 3D space and to reposition all lasts in the best manner, it is possible to utilize all 3D last models independently from design method of the shoes designers. Moreover, the sliders and heads of the FG pre-prototype move towards last's surface as expected.

The second step to enable the use of the FG pre-prototype was the determination of joint values for the configuration of all sliders. The simulation for slider positioning uses the real 3D CAD model of the FG pre-prototype to make a simulation model with IGRIP that enables to move and control all sliders as simple linear joints. An appropriate build in program allows the use of collision detection to identify position of proximity between heads and lasts. In details there are four simulation features. The first feature has been developed to load, reposition and evaluate sliders configuration for all the lasts. Repositioning is done with the simulation results of the first simulation meant for placing the lasts. These are the BB of the last and the relative position of DC relatively to the BB and to the coordinate system of the last 3D CAD model file. The next feature of slider positioning simulation has been meant to verify simulation results by loading the configuration file defined for every last and loading the relative lasts in the correct repositioning place. This feature has allowed to analyze collisions, the contemporaneous repositioning of more than a last and the measurement of differences in slider positioning. This part of the work has been the most important to validate simulation results before the use of the physical FG pre-prototype. The last feature of sliders positioning simulation has been thought to provide the simulation model with functionality of displaying the virtual shoe wearing. In this case, only the configuration file for the last is loaded and a simple inspection of the last surfaces becomes possible (Fig. 5).

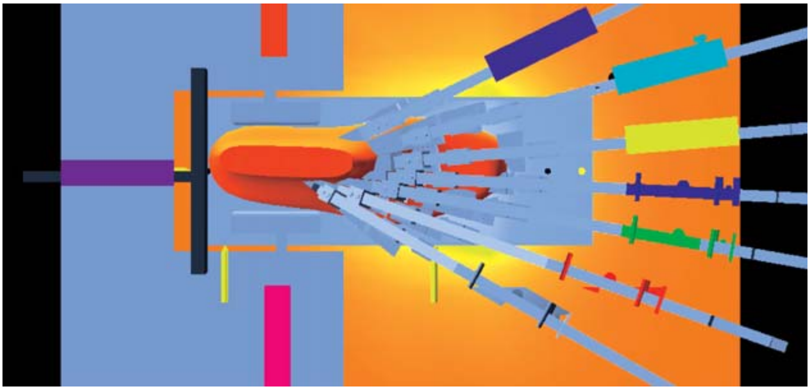

Fig. 5: Virtual test of configuration

8 Test on pre-Prototype

Some test activities have been made to validate the simulation data by comparing physical last with last's 3D model. Many physical lasts have been placed into the real FG pre-prototype according to the simulation position data. Therefore sliders have been configured using simulation data to verify position correctness of the heads respect the physical last. During this measuring phase, differences between simulation data and pre-prototype configuration have been discovered: the main difference between real and virtual values has to deal with the length of the lasts. To solve this gap we have decided to verify the dimension of physical last and to review the simulation environment to verify the data. Many people have been enrolled to test the tactile response of the FG pre-prototype, their feedbacks are now under analysis to develop solutions for improving wearability and tactile perceptions.

9 FG Conclusions

The tests have shown that FG reproduces in a good manner the volume of front upper of shoes and have given some ideas to improve the pre-prototype like cover the heads with soft material to increase the perception of wearing shoes. The test have permitted to understand what sliders are useful and what are redundant for our scope and where it is better to place them. The tests have also permitted to start a new phase of study to reduce the amount of sliders and repositioning them to make compact the next prototype. The expected results should be reduction of 30% in the amount of sliders, reduction of the weight to three or four kg for foot and finally, we expect to achieve a very compact solution. The next prototype will be designed to work with MM to simulate a real shoes try-on virtually.

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Contact Pressure Calculation Methodologies in Aeronautic Gearboxes in the CAD Process

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Abstract
This paper deals with the various methodologies usable in a CAD environment for the calculation of contact pressures in aeronautic gearbox bearings. These methodologies may be analytical (Hertz theory), numerical (F.E.M.) or hybrid. They are analyzed and compared according to their precision, calculation time and readiness to be integrated in the industrial design process. An optimum contact pressure calculation methodology will be presented based upon the results of this analysis.

Keywords
Bearing, CAD, Finite element method, Hertz theory, Gearbox

1 Introduction

In mechanical design, bearings are among the parts most widely used to link rotating sub-assemblies. Knowing how they operate is essential for designing mechanisms and ensuring their reliability. ISO standards, as well as the catalogs of bearing manufacturers, are used by designers to incorporate the component into a mechanism. In the field of aeronautics, it is essential to optimize performance while minimizing the aircraft weight. Structures are thin and deformable. A gearbox with a weight of 300kg, capable to transmit several megawatts of power is shown on figure 1. The assumptions used for the conventional calculation of bearing service life are no sufficient. It is necessary to make a complete modeling of the mechanism to take into account parts stiffness, bearings clearances, contacts, and geometrical defects. This type of calculation can be performed by bearing manufacturers, based on certain simplifying assumptions. Each bearing manufacturer has developed the tools required to perform this type of calculation. Currently, bearing dimensioning is performed in two steps. First, the designer dimensions bearings by following the conventional service life method and standard practices. Then, the bearing assembly obtained is sent to the bearing manufacturer for a dimensional verification using the manufacturer's calculation tools. It will be of interest for the designer to have this type of tools available in the CAD environment to optimize the mechanism and the design process. In aeronautics, bearings are dimensioned under the maximum contact pressure, while ensuring that maximum speeds are not reached. The aim of this study is to present a calculation method of contact pressures on integrated bearing raceways by including the deformations and geometrical defects of all the mechanism parts. This method shall be integrated into an industrial CAD software application. In this paper, all the methods, or combinations of methods, enabling calculation of contact pressures in a mechanism bearings are developed. We will analyze whether these methods take into account parts deformations and whether they can be integrated in a CAD environment.

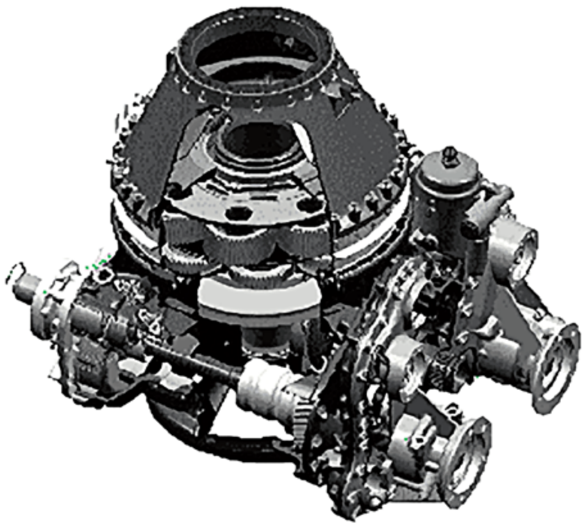

Fig. 1: 3D View of a Helicopter Main Gearbox

2 State of the Art in Bearing Calculation

Professor Stribeck was one of the first scientists to publish papers on the calculation of load distribution in bearings. In his report [2], he presented a study of the ball - raceway contact by correlating Hertz contact theory [1] with several series of tests. He obtained a relationship between the radial load applied on the bearing and the load applied on the most stressed rolling element. His work served as a basis for ISO 76 standard [3] dealing with the calculation of the static load ratings. Lundberg and Palmgren [4] studied the fatigue behavior of bearings, which led to the definition of a fatigue dimensioning criterion. Their work was used to prepare ISO 281 standard [5]. A major breakthrough in the knowledge of bearing behavior occurred in the middle of the 20th century, thanks to the work of Jones [6, 7]. His work dealt with static and dynamic behaviors. It was generalized by Harris [8] and is the basis of all theoretical studies on bearings.

The conventional method proposed by Harris is based on the assumption that a bearing deformation is due only to local crushing in the contact zones. This assumption is no longer valid if the bearing rings have a thin section. In Harris and Jones paper [9], the conventional method has been modified by using flexibility coefficients to account for the deformations of epicyclic planet gear bearing rings. Zupan [10] generalized this approach by using Finite Elements to calculate the structure flexibility matrix to account for deformations. Bourdon et al. [11] and [12] have developed a hybrid model where the mechanism is discretized into finite elements. The rolling elements of each bearing are replaced with non-linear finite elements joined to the two rings. The work of Lovell et al. [13] on the contact between a ball and two parallel plates showed that with finite elements the results obtained are close to the results obtained with the Hertz theory. Zhao [14] used a 2D Finite Element contact code to calculate the load distribution in a bearing subjected to a radial load. Kang [15] introduced a modification to the Hertz contact law, with a law derived from local contact modeling using finite elements.

According to published works, three main methods are used: analytical, numerical and hybrid. Under current conditions, these methods do not meet the requirements imposed by the scope of the study. In the following paragraph, the methodologies proposed in published works are described and adapted to the constraints of aeronautic mechanisms.

3 Methodologies Proposition

3.1 Physical Problem

The calculation of F_i loads applied at the supports in terms of the external load F is not easy without making the assumption of infinite stiffness and simplified links in the study of a mechanism (Fig 2). Each load F_i depends on the resultant of external loads F, housing and shaft stiffness, each bearing overall stiffness and geometrical defects (coaxiality, perpendicularity, etc.). However, due to contacts, the bearings overall stiffness is not constant. It depends on: load F_i, number of rolling elements, play, internal geometry, materials, and geometrical defects. Problem-solving without the assumption made cannot be direct. The solution must be iterative. In the following paragraph, several methods likely to solve this problem are developed.

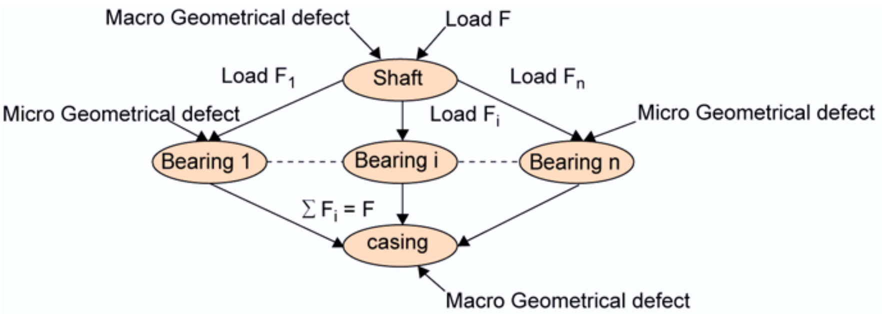

Fig. 2: Load Transmission in a Simple Mechanism

3.2 Method 1: Usual Analytical Method

It is the first method developed for the fine modeling of bearing assemblies. This method is widely used in the programs of bearing manufacturers. The analytical approach to the problem imposes to make simplifying assumptions on the deformations of parts. The shaft is modeled as a deformable beam with variable section, the housing is assumed to be rigid, and the deformation generated in the bearings is derived from local contact deformations only. To calculate contact pressures, the following assumptions may be made:

- Frictions and interactions with the lubricant are considered insignificant
- Dynamic forces are considered insignificant (low rotation speed)

Given the above assumptions, the equations for solving the problem are:

- For the shaft: static equations and behavior law (1D modeling)
- For the bearings: static equations, Hertz contact law, and the relationship between local contact deformation and the relative displacement between inner and outer rings.

The shaft equations are conventional equations, while the bearing equations are derived from a contact / displacement relationship. Bearing equations are given hereunder.

Tab. 1: List of symbols

F_r , F_a , M Bearing applied loads ϕ : Angular spacing between moment M and radial load F_r. Z : Number of balls Q_i : Ball i - raceway normal load K : Contact stiffness between ball and raceways	α_i : Contact angle ψ_i : Azimuth angle in plan xy δ_i : Contact deformation between ball i and raceways δ_r : Radial distance between inner ring and outer ring δ_a : Axial distance between inner ring and outer ring θ : Deflexion angle between inner ring and outer ring

By balancing the bearing inner ring, figure 3b, the following equations are obtained:

$$F_r - \sum_{i=1}^{i=Z} Q_i \cos(\psi_i)\cos(\alpha_i) = 0 \quad ; \quad F_a - \sum_{i=1}^{i=Z} Q_i \sin(\alpha_i) = 0 \qquad (1); (2)$$

$$M - \frac{1}{2} dm \sum_{i=1}^{i=Z} Q_i \sin(\alpha_i)\cos(\psi_i + \frac{\pi}{2} - \varphi) = 0 \qquad (3)$$

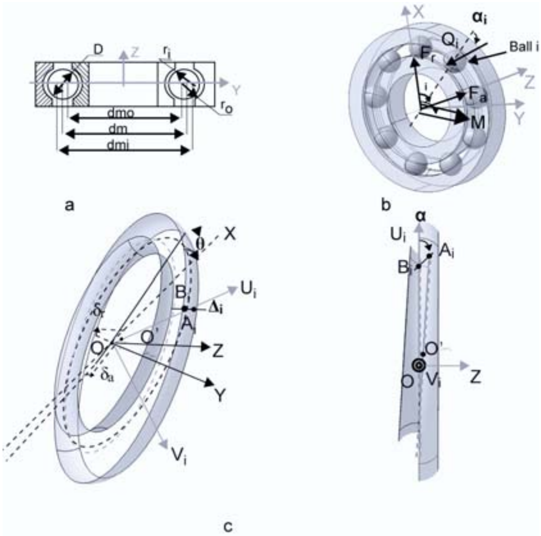

Fig. 3: a) Bearing geometry; b) Bearing loads; c) Relative displacements between inner and outer rings.

By successively applying the Hertz theory, to the contacts between the inner raceway and ball i, and between ball i and the outer raceway, the following formula is obtained:

$$Q_i = K \cdot (\delta_i)^n \tag{4}$$

The relationship between local contact deformations of ball i and overall relative displacement between inner and outer rings is as follows:

$$\delta_i = \sqrt{\left(ri + ro - D - Pd + \delta_r \cos\psi_i\right)^2 + \left(\delta_a + \frac{1}{2}\, dmi\, \theta \cos(\psi_i + \frac{\pi}{2} - \varphi)\right)^2} - (ri + ro - D) \tag{5}$$

With, Pd being the diametral play (Pd = (dmo + 2 ro) - (dmi + 2 ri) -2D)

Equation (5) is obtained by calculating the distance between point Ai (intersection between the mean circle of the outer ring and plane U_iZ) and point B_i (intersection between the mean circle of the outer ring and plane U_iZ) before and after the displacement of the rings. The local deformation due to ball i contact is given by the difference of distance $[A_iB_i]$ before and after displacement, taking into account the initial diametral play. Ball i contact angle is given by the direction of straight line (A_iB_i) on plane U_iZ. The following relationship is obtained:

$$\sin\alpha_i = \frac{\delta_a + \frac{1}{2}\, dmi\,\theta \cos(\psi_i + \frac{\pi}{2} - \varphi)}{\sqrt{(ri + ro - D - Pd + \delta_r \cos\psi_i)^2 + \left(\delta_a + \frac{1}{2}\, dmi\,\theta \cos(\psi_i + \frac{\pi}{2} - \varphi)\right)^2}} \quad (6)$$

The overall problem-solving is done by applying the Newton-Rapthon iterative method.

This analytical method is fast but does not take into account all deformations existing in the mechanism (housing deformation, bearing raceway deformation). It cannot be applied for the aeronautic mechanisms under study. However, the method can be used for local behavior modeling while the overall behavior will be obtained using other approaches.

3.3 Method 2: Hybrid FEM and Analytical: Using Stiffness Matrix

The problem formulation is the same as for method 1. The contact management is done analytically. Deformations of the mechanism parts are accounted for by introducing the flexibility matrix [P] of the mechanism in equation (6), which now reads:

$$\delta_i = \left[\sqrt{(A - P_d + \delta_r \cos\psi_i)^2 + \left(\delta_a + \frac{1}{2}\, dmi\,\theta \cos(\psi_i + \frac{\pi}{2} - \varphi)\right)^2} - (ri + ro - D)\right] + \left[[P]\cdot F\right]_i \quad (7)$$

Where F is the vector of the external loads and unknown Q_i contact loads of each bearing. P is the structure flexibility matrix.

Before performing the overall problem-solving, it is necessary to calculate the flexibility matrix by using finite elements.

$$KU\text{-}F = 0 \quad (8)$$

The flexibility matrix P ($P = K^{-1}$) is calculated by solving equation (8) for various unit load cases. This method was used by Zupan et al. as explained in paper [10], for a simple mechanism having a single bearing. With more complex mechanisms, this method shows very quickly its limits in terms of calculation time and required memory space. For these reasons this method has not been used in the present study.

3.4 Method 3: Hybrid FEM and Analytical: Using Contact Code

Today, most finite element software applications can manage contact between parts. Several methods are available, but the most widely used in calculation codes are the Lagrange multipliers, the augmented Lagrangian and the penalty methods. In this model, contact is modeled by applying a linear law and calculation is done assuming small disturbances. To obtain good results with this type of modeling, it is necessary to make a fine and symmetrical meshing of contact zones. For the present study, an optimized meshing of the bearings (Fig. 4 a, and b) was done to find the best compromise between the quality of results and calculation time.

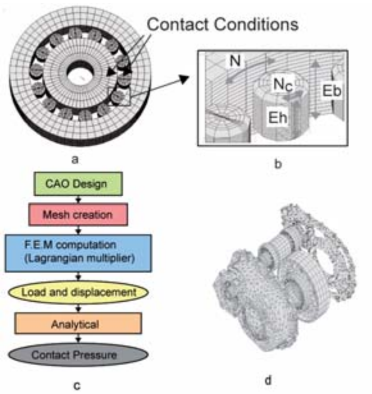

Fig. 4: (a) Optimized meshing of a roller bearing; (b) Parameterization of meshing optimization; (c) Flowchart describing the method developed; (d) Meshing of the input mechanism of a helicopter gearbox.

In the finite element modeling, two contact conditions have been introduced for each rolling element of a bearing: A contact condition between a rolling element and the inner raceway and another between a rolling element and the outer raceway. For a roller bearing having 5000 nodes and 100 degrees of freedom of contact, good results have been obtained in terms of loads and displacements. However, the contact pressure results are unusable (too few elements in the contact zone). The approach developed for the calculation of a complete mechanism is described by the flowchart in figure 5 c. This approach consists in computing the mechanism using finite elements (Fig.5 d) with an optimized meshing of the bearings, retrieving the loads and displacements of each bearing and calculating contact pressures by applying an analytical method (see paragraph 3.1).

With the methodology developed, it is possible to obtain the contact pressures in the bearings by taking into account the deformations of all the parts of the mechanism. This methodology can be readily implemented in a CAD environment. Parts drawn using the CATIA V5 software are retrieved and drawn with the SAMCEF finite element software. Moreover, calculation times are not excessive (approximately 3 hours for a gearbox with 4 reduction stages). A program has been developed to retrieve finite element results and to calculate contact pressures.

3.5 Method 4: Hybrid FEM and Analytical: Using Rolling Elements

Modeling of the mechanism is done by finite elements with no contact conditions. Contacts are replaced with macroelements (Fig 5 a). This method is derived from the work of Bourdon et al.. [11, 12]. In these papers, the contacts between rolling elements and raceways are modeled by non linear beams joined to the raceways. Problem-solving is non-linear.

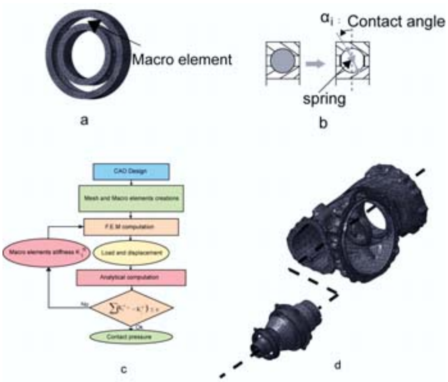

Fig. 5: (a) Meshing of a roller bearing with springs; (b) Spring modeling; (c) Flowchart describing the method developed; (d) Meshing of the lateral mechanism of a helicopter gearbox.

Contrary to Bourdon et al., the proposed method replaces the contacts between rolling elements and raceways with linear springs directed as shown in figure 5 b. At each iteration, the finite elements calculation of the mechanism is linear. Spring stiffness and direction are recalculated at the end of each iteration. Convergence is obtained when the difference between the sums of the stiffness of springs n+1 and n is lower than 0.1%. The mechanism problem-solving is done using the finite element module (GPS) of

CATIA V5. The springs stiffness and direction (contact angle) are calculated using equations (4), (5) and (6) and a CATIA macro. As a rule, the solution converges after a few iterations (about 10). Contact pressures are directly derived on completion of the calculation.

With this methodology, it is possible to obtain the contact pressures in the bearings by taking into account the deformations of all the parts of the mechanism. This methodology also offers the advantage of being directly implemented in a CAD environment (CATIA V5).

4 Comparison Methods

In the above paragraphs, 4 methods are proposed to calculate the pressures exerted between rolling elements and rings. The analytical method does not allow for the inclusion of the mechanism structure overall deformations. This specificity renders the method obsolete for the problem analyzed. The second method is a hybrid method combining an analytical method with finite elements where the structure stiffness is accounted for via a flexibility matrix. The calculation of the flexibility matrix requires large computation resources since a very large-size matrix is required for the structures treated. The third method is based on a hybrid calculation using finite elements in a first step and an analytical approach in a second step. This method was implemented and successfully tested on actual problems. The last hybrid method is based on finite elements calculation where contact is described with springs, the stiffness and direction of which are calculated by analytical method. This method gave very good results on dynamic components. In conclusion, only two methods meet the constraints of the aeronautic environment.

An experiment was carried out to compare the two methods as regards the relative accuracy of the results obtained. First, a simple structure is assumed to be rigid (9-ball bearing subjected to an 8900N radial load at ball 1). In this case the analytical method can also be used. This experiment compared the two methods developed with the analytical method used by bearing manufacturers. The results obtained during this experiment are shown in figure 6 a. Similar values are obtained with the three methods. The difference between the maximum calculated pressures is lower than 1%.

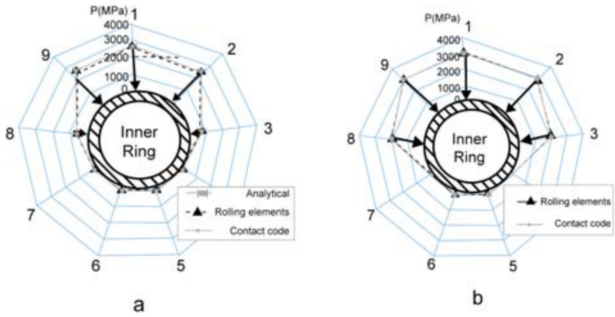

Fig. 6: (a) Pressure distribution graph for a rigid structure; (b) Pressure distribution graph for a flexible structure

In the second step, the structure deformability was taken into account. The results obtained during this experiment are shown in figure 6 b. The two proposed methods gave similar results. The maximum variation between the two estimation is 3%. The difference in the distribution of the maximum pressures applied to the inner raceways observed in the two cases presented is of particular interest. Taking into account the deformability of the bearing rings decreases the value of the pressure exerted on the most stressed rolling element (ball No. 1) by 10%. The two methods shall be integrated in the gearbox design process. One method uses software (SAMCEF) external to the CATIA V5 design line. SAMCEF and CATIA V5 will need to be interfaced for the two programs to communicate. The other solution proposed is fully integrated into CATIA V5.

5 Conclusions

In this paper, a bibliographic study is offered to highlight four methods usable to determine the contact pressures between the rolling elements and raceways incorporated in an aeronautic mechanism. Two of these methods were deemed unsuitable for the objectives set. The two other methods were analyzed, improved and adapted to the aeronautical environment. Their results and their implementation in a CAD environment were compared. This comparison revealed the similitude of the results obtained and the perfect adaptability of one method to the work environment. In addition, the positive impact of the structure deformation on the contact pressure distribution has been highlighted. These studies are the first steps before the introduction of geometrical defects in the mechanism. This will be the subject of further research activities.

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Common Representation of Products and Services: A Necessity for Engineering Designers to Develop Product-Service Systems

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Abstract

From a couple of years now, a new selling approach is emerging from European enterprises. They are now more focused on providing services rather than selling physical products, or on selling more added services with products. The Product-Service System (PSS) principle is used to call these embedded sets of product and services in which the ratio between product and services can vary to satisfy the customer. But the development of these new sets is almost made by developing scenarios of the use. The problem is to translate these scenarios into products and services criteria for the engineering designers. This article will present a methodology based on Functional Analysis in order to support the development of products and services included in a PSS.

Keywords

Product-Service System (PSS), design representation, functional analysis, characterization.

1 Context and Problematic

A product is developed to fulfil customer's needs. But once those needs change or disappear, the customer discards the product. By providing the use of the product when required by the customer, it is easier to fulfil changing needs or new needs at the right moment. It is the reason why the European market is shifting from selling products to providing services [12].

In that case, there is a service contract and the customer is not anymore the owner of the product. When he will terminate the contract with the service provider, this service will be available for another customer or another application and the product won't be discarded. These new sets of products and services fulfilling customer's needs are named Product-Service Systems (PSS), in which the ratio between product and services will vary [6]. This could decrease the creation of waste and decrease the consumption of raw materials [4]. On the other hand, it will lead to the dematerialisation and creation of sustainable products [7]. From the engineering designer's point of view, the development of these new sets of product and services will transform the way to design [10]. Usually, engineering designers develop either products or services but in the case of PSS they have to develop both product and services within an integrated design process [8]. But for the moment, there is no representation for these sets [9].

The main methods to develop the PSS are based on blueprint [5] and the definition of scenario [13]. Once the scenario is validated, designers have to create products involved in the scenario. But between the description of the scenario and the development of these objects there is still a gap because the scenario does not give criteria about the products to design. Consequently it is necessary to develop a methodology to support the development of PSS. In order to fill this gap, we propose to use the functional analysis representation to characterise PSS and by the way help designers during the design process of products and services included in the PSS.

The next section will describe the functional analysis principle, detail tools and concepts used for the description of PSS. A PSS example will be described with this methodology. It is a French example: a renting bike service called Vélo'v that is used in Lyon.

2 Functional Analysis of a PSS: the Vélo'v Example

Designers, who have to represent a product during the whole design process, can use a functional approach and in particular Functional Analysis [1, 2, 3]. The Functional Analysis method considers the expression of the needs of the various actors of the product life cycle as essential. This method proposes different concepts (functions, constraints, assessment criteria) and tools (Graph of Interactors, FAST, etc...) to make them work and construct relations between needs and constraints, service functions, technical functions and solutions, stage by stage.

To explain how this method works, the case study Vélo'v will be used. Vélo'v is a new rental bicycle service in Lyon, France. This new service proposes to the customer several renting points where he can rent and bring back bikes. To move from one point A to another point B, the customer rents a bike in a station near A and can bring back the bike in another station near B. He is only charged for the time of use. The difference with a classical rental system is that the customer is not forced to bring back the bike at the initial renting point.

2.1 The External Functional Analysis for the Vélo'v Example

External functional analysis lists the services that the product has to provide irrespective of the means available to provide them. The product is, at this point, considered as a black box, which is able to satisfy customer's needs and those of the professionals involved in making it [11]. It is described in terms of service functions and constraints:

- The interaction function (IF) that corresponds to the services provided by the product during the product life cycle;
- The adaptation function (AF) that reflects reactions, resistance or adaptations to elements found in the outside environment.
- The constraint is defined as a design characteristic, effect or provision for design, which is made compulsory or forbidden for whatever reason.

Vélo'v is installed in the city of Lyon. The stations, where bikes are stored, are spread in the city among all others objects (walkers, pavement, etc.) and the customer rents a bike in a station. By looking at all elements that are external to the renting service, it is possible to detail 3 outer environments: the city in which the renting service is installed, the customer whom will use the service and the external environment of the service. This last element is composed of the climate and the road-user. By representing the PSS with an external functional representation (see figure 1), it is possible to highlight the "link" between those elements and the PSS to develop. The link will be the service functions, or external functions, required by the customer.

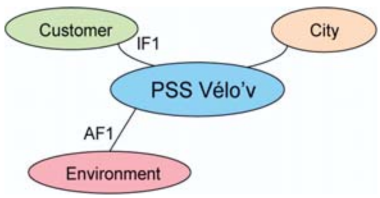

Fig. 1: Graph of interactors for Vélo'v

Before highlighting functions, it is important to characterise the outer environment. This characterisation will help the emergence of supplementary functions expected by the customer. In our case, the functions can be detailed as:

- IF1: the PSS enables the customer to move in the city. Two others adaptation functions which are “the PSS must be adapted to the customer” and “the PSS must be adapted to the city plan” are implicit;
- AF1: the PSS must be adapted to the environment (climate and road-user).

On the other hand, projects are always forced to respect some constraints. These constraints are available all along the development of the project and must be respected for each choice of solutions. Instead of indicate outer environment that influences the product to design, it is also possible to indicate constraint that must be respected during the whole design process. When a product is developed, the three most important constraints are cost, quality and time-to-market. In the case of Vélo’v, only two constraints are indicated:

- C1: the product must be manufactured by the current manufacturer;
- C2: the costs.

It means that designers must at any time during the development consider those constraints. Each service function and constraint must be characterized to help designer to find the right compromise about the product. This characterisation takes into account several elements of the outer environments and considers the characteristics of the action between the PSS and the outer environments. For example, Table 1 is the partial description of the interaction function 1 “the PSS enables the customer to move in the city”. In this table we have criteria about the customer and the city involved in the function, and criteria for the action (in this case “move”).

The characterisation of service functions permits to engineering designers to have external criteria. Those criteria are necessary to justify the technical solutions that will be used afterwards in the internal representation. For each criterion, allowance must be indicated. This allowance will allow a tolerance in the level for the criterion. Once all service functions are described in tables, engineering designers try to define the technical functions that are necessary to achieve the external functions.

Tab. 1: Characterisation of IF1

Criteria	Level	Allowance
Customer		
Man or woman	> 14 years old	…
Health	No handicap	…
Language	French or not	…
Etc.	Etc.	Etc.
City		
Average temperature	X °C	+/- 2 °C
Number of rainy day	X day	+/- 5 days
Kind of surface	Road, cobblestone, other	…
Etc.	Etc.	Etc.
To move		
Life span	X years	+/- M months
Average distance between places	X km	…
Average time between places	X mn	…
Etc.	Etc.	Etc.

2.2 The Internal Functional Analysis for the Vélo'v Example

Internal functional analysis, or technical functional analysis, enables designers to analyze the resources necessary to provide the service required, identified in the external analysis. Two tools have been chosen to make an internal product analysis: the FAST (Functional Analysis System Technique) and the Functional Bloc Diagram.

FAST: from Technical Function to Solution

Once the service functions (interaction and adaptation functions) are identified in the external functional analysis, the engineering designer has to decompose these service functions into technical functions and then into solutions. The FAST diagram represents this decomposition.

Currently, designers are used to detail functions and to find components that will fulfil the function. But in the case of PSS, there are not only physical components that will fulfil this function, but both physical products and technical service units will ensure the functions.

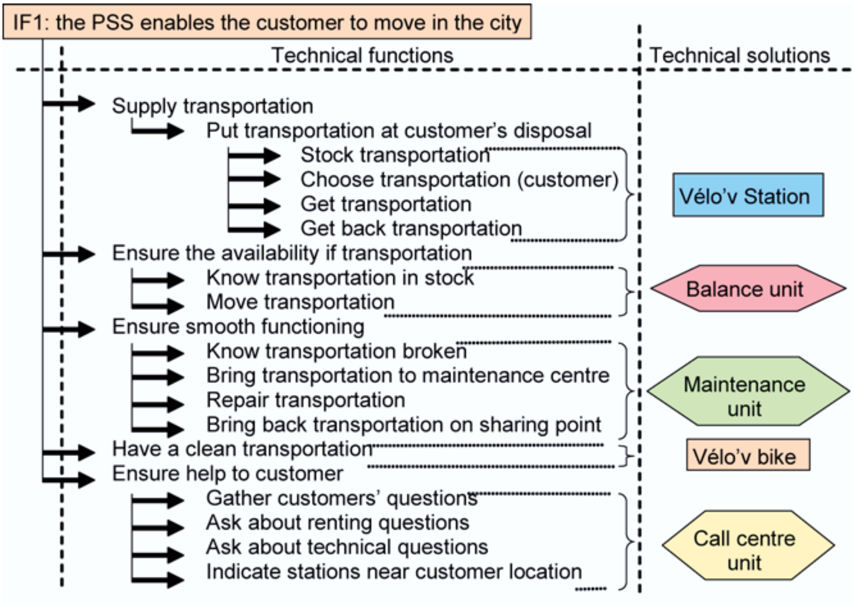

Fig. 2: FAST diagram of interaction function 1

In figure 2, the interaction function 1 is decomposed. In this representation, both products and services appear. Physical objects are symbolized with rectangle, while technical services are represented with hexagon. The contribution of this tool is to realise the representation of physical objects and technical services in a same model. Until now, designers only represent products or technical services, but there was still a gap to represent both.

Once the solutions are chosen to realise technical functions (right side of FAST diagram), the Functional Bloc Diagram is used to represent the links between these technical services and products.

Functional Bloc Diagram

The Functional Bloc Diagram (FBD) gives a schematic formalism of the product with the different components, the links between them, the functional flow and the flow concerning design choices. In the case of PSS development, those components can be either product or service. It is a mean to consider not only functional and technical components characteristics but also the interaction between components and especially the main functional flow of the product. With the FBD we can have some information about:

- The different components of the product and particularly, those necessary to the function realization;
- The contacts between the components;
- The design choices (Design Buckle (DB)) that are for example technical solutions used to assemble components or to put them in position. In the case of PSS solution, the design buckle can represent organisational choice including products and services.

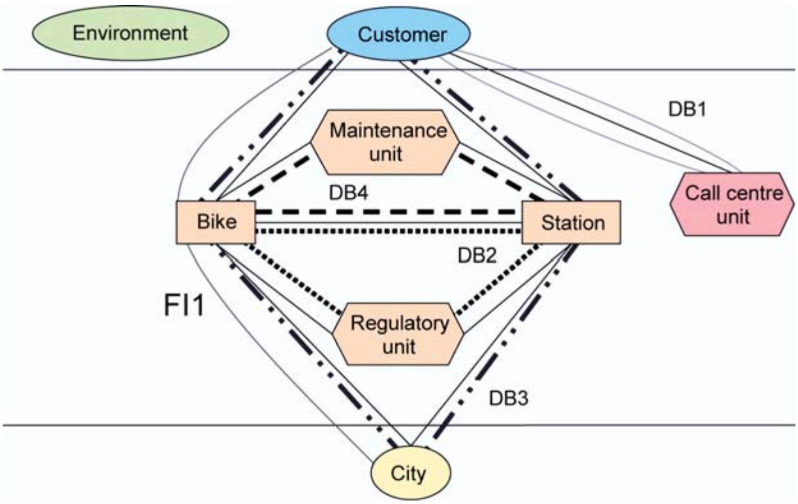

Fig. 3: FBD of Vélo'v example

In the FBD (see figure 3), links between objects and services are detailed. It can be physical links, links due to information flow, virtual links (e.g. visual or hearing test), etc… For example, the maintenance service that repairs bikes will be linked to the station to take and bring back bikes. Moreover, bike and station are also linked due to the physical link between the storage area and bicycle. Consequently, in this particular representation we can have either links between physical objects, or between object and service. It would be also possible to have link between two services if for example the call centre unit would give information to the maintenance service about the broken bikes. These main entities (physical objects and technical service units) and links reflect the scenario of system functioning. By representing IF1, this function will go from the customer to the city by passing through the bike. But, in order to fulfil this function, technical functions and solutions are necessary. The components realise only the "primary" technical functions. This is an overall organisation that makes work the technical function. The design buckles represent it. As components are linked themselves, this is not only the component but also a global relation that realises the technical function. The FBD details 4 design buckles:

- DB1: ensure help to customer
- DB2: ensure the availability of transportation
- DB3: supply transportation
- DB4: ensure smooth functioning of transportation

In a design buckle, both products and services are linked. It will be necessary to detail each link because the components will influence themselves. In order to do that, designers have to implement criteria about this link. The criteria for relations will be a mean for designers to integrate constraints during the development of elements and consequently to optimized the overall set of product and services.

3 Conclusion and Outlooks

At present, PSS methodologies are based on describing scenarios but for designers there are no tools to support the development of physical products and technical service units included in PSS. Based on functional analysis, this representation enables engineering designers to represent PSS from customer's needs to a particular solution of products and services. The key elements in this representation are the criteria detailed all along the representation. All criteria are means of discussion and implementation between the development of products and services.

The external representation enables the engineering designer to detail the functions expected by customer and external criteria. The internal representation goes deeper in the PSS solution. It enables to detail technical functions and show the primary products and services that will fulfil them. These functions are based on external criteria. Moreover, it enables to map the relation between components and detail once again criteria that will enable to develop in an integrated way products and services.

As PSS brings a new value for the customer, maybe the product involved in a PSS is different from a product sold to a customer. Perspectives are to compare these 2 products and highlight what will influence the choice of technical solutions.

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Toward Design Interference Detection to Deal with Complex Design Problems

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Abstract
This paper proposes a method to deal with complex design problems typically found in multi-disciplinary design such as mechatronics design. First, it explains two different types of complexity, namely *complexity by design* and *intrinsic complexity of multi-disciplinarity*, typically found in mechatronics design, from the viewpoint of knowledge structure. Second, a mechatronics design case illustrates how these types of complexity lead to undesired and unpredictable interactions that cause destructive decoupling of subsystems. Third, we present a technological way to detect such undesirable interactions at an early stage of design based on a qualitative reasoning technique.

Keywords
Complexity, Multi-Disciplinary Design, Qualitative Physics

1 Introduction

The complexity of product development has increased tremendously in two aspects. The product complexity has increased, first because of rapid technological developments, and second because products have become significantly multi-disciplinary or even inter-disciplinary. The product development process, too, is becoming complex, because more stakeholders are involved and their roles are rapidly changing as well. These two types of increasing complexities, viz., product complexity and process complexity, make the product development of modern products extremely difficult. Consequently, product development teams are under great pressure in a competitive market with respect to not only functions, cost, and quality, but also speed (time-to-market and time-to-delivery), sustainability, and product-service systems [9]. Among others, we cannot underestimate the impact of the multi-disciplinary or inter-disciplinary nature of modern products, such as mechatronics machines, on the complexity of product development processes. Nowadays many mechanical systems are based on the mechatronics principle; it might be virtually impossible to find out a mechanical system (not a component) that is not controlled or monitored by a CPU or does not have LED/LCD displays for easier operations.

But, then, why are such multi- or inter-disciplinary product development processes so difficult? There can be many answers, but one interesting answer can be that the structure of our knowledge system is the source of difficulties of multi-disciplinary product development. Engineers and designers are educated and trained discipline-wise, such as mechanical engineering, electronic engineering, and software engineering. These engineers and designers, therefore, become domain experts, for example, mechanical engineers whose knowledge system becomes rich with the knowledge in mechanical engineering. Since they have less knowledge about, for example, electronics, team working or collaboration with experts in other domains becomes mandatory for developing multi- or interdisciplinary products such as mechatronics.

Collaboration of experts from different disciplines can bring in three types of difficulties. First, there can be no common language, i.e., ontology problem. The second is process complexity to deal with many stakeholders in the process. Third, since there is no one who truly understands inter-disciplinary problems, some problems can fall into a gap between experts. This type of problems caused by interactions among different domains could be hard to solve (because no one is an expert) or even hard to detect.

This paper is an attempt to attack this third difficulty inevitably associated with multi- or inter-disciplinary product development. In the next section, we argue that the structure of our knowledge system is the source of complexity. We then identify two different types of complexity in multi-disciplinary problems; *complexity by design* and *intrinsic complexity of multi-disciplinarity* [8].

Then, we will discuss methods to manage complexity in multi-disciplinary product development. To do so, a mechatronics design case illustrates how these types of complexity lead to *undesired* and *unpredictable* interactions that cause destructive decoupling of subsystems. We will look at a design using a rotary encoder. While this is a simple and commonly used component, it still requires good caution to use when precision really matters. Well-known techniques to deal with complexities are Design

Structure Matrix (DSM) [1] and Suh's Axiomatic Design (AD) [6]. Suh extended AD to deal with complexity in design recently [7]. However, these methods cannot deal with cases well in which the complexity increases unexpectedly during the course of design due to *undesired* and *unpredictable* interactions among subsystems.

To tackle this problem, we present an idea to use qualitative physics [11] to detect those unpredictable interferences among subsystems. We will propose a method based on Qualitative Process Theory [2].

2 Multi-Disciplinarity and Complexity

2.1 Difficult Mono-Disciplinary Problems

Before we discuss the relationship between multi-disciplinarity and complexity, it is important to understand that even mono-disciplinary problems can be hard to solve. For instance, if the number of design parameter becomes extremely big (maybe in proportion to the number of components or complexity of the shape), computational complexity makes the problem hard to solve. Another type of mono-disciplinary difficulty is the case in which the governing equations have difficult forms to solve, such as non-linear partial differential equations [8].

Compared with simple design problems in which the classic divide-and-conquer strategy is valid, these problems cannot be solved in a straightforward manner. If subdividing strategy does not work, the problem size remains the same and perhaps computational complexity-wise even brute-force approaches, such as a generate-and-test method, become prohibitive to execute.

2.2 Complex Multi-Disciplinary Problems

On the other hand, the multi-disciplinary nature of modern products exhibits another type of difficulty in product development. When multiple domains are involved in a design problem, unless there is a uniform theory that can attack the problem as a whole, we will be forced to use a set of theories (or knowledge systems or even domain experts) each of which is valid only in one domain. Although these theories are in principle independent from each other, they can have (sometimes even) intrinsic interactions with each other for a variety of reasons (which will be illustrated later) [8].

These interactions among theories indicate the existence of multi-disciplinary problems. For instance, consider a design problem of an oscillating beam. If the amplitude of vibration is relatively small and thus the strain remains small, we may not need to take into consideration such phenomena as plastic deformation, fatigue, hardening, and fracture. At an abstract level, this is a typical situation in which interferences among different physical domains become non-negligible and different domain theories have to be considered.

When these interactions are well-known before the design takes place, we can take counter-measures. However, if unknown or unidentified, at a later stage the designer will be surprised by those hidden or neglected interactions between theories. Once this type of interactions is detected, the designer will be forced to perform undesired design changes or even to re-design from the beginning. These will delay the project significantly and thus have strong cost implications.

In the following section we look at these interactions among theories associated with multi-disciplinary from the viewpoint of relationships among theories, i.e., knowledge structure [5, 8].

2.3 Relationships among Theories: Knowledge Structure

Complexity by Design

To understand the complexity resulting from the involvement of multiple disciplines, in this section we examine the structure of knowledge represented by relationships among theories. Here, a theory denotes a self-contained axiomatic system consisting of a number of axioms and concepts (or terminology). The relationships among these concepts are defined by axioms and theorems derived from axioms. A theory is a mono-discipline system by definition and can represent only a piece of knowledge about one discipline.

Two theories can have different relationships with each other. In the following, we will examine these situations. Two theories are in principle independent, because if not independent, that means the axioms of the two theories are overlapping each other. However, this is only syntactically true and two theories can have different types of semantic relationships.

The first case is a situation in which two theories can have relationships because of designation (or instantiation) of entity. Fig. 1 illustrates such a situation. Newtonian mechanics forms a theory that begins with the law of universal gravity and three laws of motion. Knowledge of a class of mechanical component (such as spur gear) also forms a theory that contains such statements about its functions and attributes as "a spur gear pair transforms mechanical rotational power" and "the moderation ratio is determined by the ratio between the numbers of gear teeth of the pair". During a design process of gear pairs, the designer considers the numbers of teeth of a particular gear pair, instead of the ratio of pitch diameters, because he/she designated (or instantiated) a gear pair as a means to transform mechanical rotational power rather than pulleys. In other words, at the moment of the designation of a particular spur gear these two theories of mechanics and of machine elements share a common concept, i.e., a spur gear. This creates a connection between these two theories and because of this connection the whole knowledge system has additional complexity.

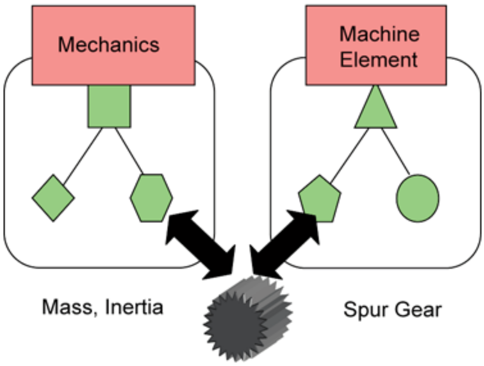

Fig. 1: Two theories are independent, but share one physical object by designation in different context

We call this complexity *complexity by design*, because the designer chose a gear pair. If we chose a hydraulic solution to transform energy, different theories would be incorporated.

Intrinsic Complexity of Multi-Disciplinarity

Although independent, two theories can contain the same concept as depicted in Fig. 2. An example is motor design in which dynamics and electromagnetics can be related with force as a sole interface parameter. These theories are closely related knowledge systems *intrinsically*, because it is not a design choice but physics that determined the linkage between these theories. This is the case often observed in multi-disciplinary product development and can be called *intrinsic complexity of multi-disciplinarity*.

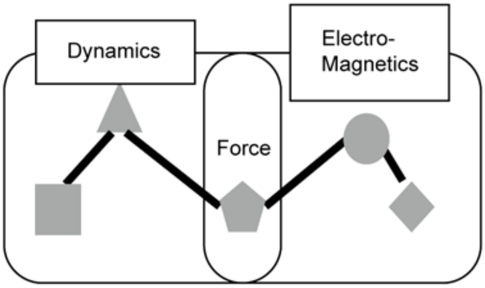

Fig. 2: Two theories share a physical concept

There can be special cases of Fig. 2. For example, elasticity theory and plasticity theory share some portion, but they differ in their applicable ranges. Elasticity theory is valid under a condition that the deformation is relatively small and there is a linear relationship between load and elongation, whereas plasticity theory is applicable when such a linear relationship does not exist. Another case is the relationship between kinematics and dynamics. Concepts in kinematics are totally subsumed in the concepts of dynamics, therefore kinematics is a part of dynamics.

Intrinsic complexity of multi-disciplinarity happens regardless of the choice of design object, whereas *complexity by design* happens only when designed in that way. In other words, *complexity by design* may have a way to avoid. In contrast, *intrinsic complexity of multi-disciplinarity* cannot be avoided because physics dictates in that way.

3 Design in a Multi-Disciplinary Domain

In this section, we illustrate a design case in which its multi-disciplinary causes undesired and unpredictable couplings among design parameters or phenomena, although multi-disciplinarity itself is useful to achieve superior functionalities.

Fig. 3 shows a rotary encoder used very frequently in mechatronics machines to measure (angular) speed or position. Depending on the application, an encoder with appropriate accuracy has to be selected. Although this seems trivial and easy to do, it can fail due to unpredictable coupling with other elements.

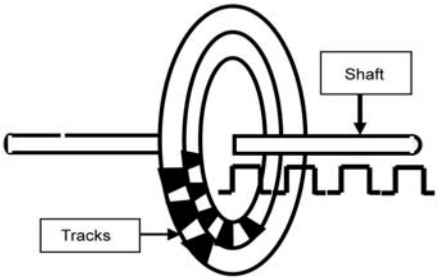

Fig. 3: Rotary encoder

For instance, an encoder is mounted on a shaft to control the angular speed of the shaft. This connection between the encoder and the shaft is necessary for the encoder to perform its function and is *predictable* and *desired*. We can call this a *constructive coupling*. The encoder contains a photo-detector that collects and transforms angular information into a signal. This connection with the photo-detector is a constructive coupling, too. The encoder is the interface between shaft and software to obtain the position information of the shaft and to control the shaft rotation.

In a real physical system, however, the eccentricity of the shaft is unavoidable and behaviors resulting from the eccentricity can disturb other parts of the system. The eccentricity provides periodic errors that will probably have the sinusoidal shape and a repetition of the fault every period. If there is a repetition of errors, we can in some way predict the error and compensate the transmitted information.

Although it might lead to a *destructive coupling*, the eccentricity of the shaft is *undesired* but *predictable,* because a good designer can predict it from experiences and come up with workaround measures. This eccentricity problem happens due to the design choice, therefore is a good example of *complexity by design*. Other examples of those undesired but predictable problems that the designer may face during the design involving rotary encoders include tilted axis rotation, radial deviation of the bearing, torsional stiffness, and axial oscillation of the track.

However, there is another type of troubles that cannot be solved easily. Suppose there is another component that operates at the same frequency of the error generated by the eccentricity. There can be interference between the two signals, which causes a peak in the frequency spectrum and the information provided by the encoder can become incorrect. Even if the eccentricity's error remains acceptable, this new situation leads to a *destructive coupling*.

One solution for this problem could be to change the frequency of one of the two subsystems, but this may result in other problems and cause a chain of problems that become too hard to fix. Another solution is to introduce otherwise a notch filter to cut off undesired signals. However, in any case, both of the solutions result in major design changes at the conceptual level that can mean extra costs and delay of the project.

4 Design Interference Detector

Technological methods should be developed to manage the two types of design complexity, *viz.*, *complexity by design* and *intrinsic complexity of multi-disciplinarity*.

One reason for *intrinsic complexity of multi-disciplinarity* is the lack of sufficiently systematized design knowledge that can tackle multi-disciplinary problems as a whole. An obvious, straightforward approach is to establish a unified theory to tackle such a multi-disciplinary design problem. To do so, first we need to build ontological knowledge that describes relationships among various theories. Such ontological descriptions about a theory will help to identify conditions in which the theory is valid and interfaces among theories. This is the approach of knowledge integration and fusion through ontological integration [9, 10, 13].

On the other hand, since *complexity by design* is caused by design choices, there is not really a good theoretical counter measure that can be prepared to help solve the problem.

However, to avoid finding unexpected relationships among theories at a later stage of design, it might be useful to develop a *design interference detector*. This system can be a qualitative physics based reasoning system [11], among others based on Forbus' Qualitative Process Theory (QPT) [2] that envisions possible interactions among employed theories caused by *complexity by design* or *intrinsic complexity of multi-disciplinarity*. An early attempt can be found in [3, 4].

The basic ideas are the following. QPT has two major knowledge elements about physical world, *viz.*, *individuals* for physical entities and *processes* for physical phenomena. A process can include such prerequisites for the process to fire as a parameter satisfying a (qualitative) condition, existence of certain individuals, and activation of certain processes. Individuals have such parameters as weight, pressure, etc. Triggering a process can change the values of these parameters.First, we build a knowledge base that contains as many physical phenomena (processes) and entities (individuals) as possible. Second, we develop a reasoning system to envision possible physical phenomena that can happen to design objects.

Since it is well known that qualitative physics based reasoning system can reason out numerous, superfluous behaviors that can be neglected, it is crucial for the system to prioritize reasoning results. For instance, it may reason out that anything in a gravity field receives gravity force in proportion to its mass. It also reasons out that anything that receives force can deforms and depending on the material property, the deformation could be, for example, elastic deformation, plastic deformation, or even brittle fracture. The tricky part of this story is that the system even warns with a scenario that there is a possibility that the machine can be destroyed by its weight, which *usually* doesn't happen. Using a qualitative reasoning system requires to remove such unlikely situations from the reasoning results.

5 Conclusions

This paper is an attempt to attack difficulties inevitably associated with multi- or inter-disciplinary product development.

In "Multi-Disciplinarity and Complexity", we argued that the structure of our knowledge system is the fundamental source of complexity. We then discussed two different types of complexity in multi-disciplinary problems; *complexity by design* and *intrinsic complexity of multi-disciplinarity*. The former basically comes from a design choice made by the designer and triggers hidden interactions among different domains. By doing so, an undesired and unpredictable problem can reveal. The latter is embedded in the knowledge system and can become a problem when unidentified interactions become major. While to avoid the former there might be design workarounds, the latter is intrinsic and cannot be avoided by simple design changes, thus it can be more difficult to solve.

In "Design in a Multi-Disciplinary Domain", using an encoder as an example, we illustrated a mechatronics design case that exhibits *undesired* and *unpredictable* interactions among subsystems. They are mostly resulting from complexity by design but can cause destructive decoupling of subsystems. We will look at design using a rotary encoder.

Then in "Design Interference Detector", we presented a method to detect such design interferences based on Qualitative Process Theory at an early stage of design. Although the system is yet to be developed, this approach seems feasible and promising.

6 Acknowledgement

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About the Efficiency and Cost Reduction of Parallel Mixed-Model Assembly Lines

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Abstract
Although Mixed-Model assembly lines have a number of advantages over Single-Model lines, they suffer from several drawbacks, such as increased assembly complexity and greater work flow fluctuations, mainly due to the differences between the models assembled in the line. This research has adopted a new approach to cope with the above disadvantages in which the models are clustered into several assembly lines. The research presents a Model Partitioning and Clustering Algorithm (MPCA), which determines the similarity between models and assigns them accordingly to different parallel assembly lines. Empirical analysis shows that the MPCA can find a better solution than the optimal solution for one Mixed-Model line, which assembles all the models simultaneously.

Keywords
Manufacturing System, Assembly Lines, Heuristic Method

1 Introduction and Literature Review

Assembly lines, which are used to perform massive assembly operations, have three main advantages over assembling an entire product by a single worker: short transfer time between assembly tasks, increased efficiency of tools and machinery, and a low level of skills needed from workers (Askin and Zhou, 1997). Therefore, assembly lines benefit from low production costs, short cycle times and improved product quality (Simaria and Vilarinho, 2004).

A factory that mass produces several similar products usually will operate a Mixed-Model (MM) line, which assembles products simultaneously in proportion to demand to avoid producing products in batches. Compared to MM lines, batch production suffers from large inventories, costs of transfer between models and inefficiency in meeting ever-changing customer demands (Lehman, 1969; Simaria and Vilarinho, 2004). On the other hand, the use of MM lines increases assembly complexity, makes it harder to divide work equally among stations and demands greater training time for workers because of differences in model characteristics. Thus, MM lines suffer from delays, holdbacks and starvations in the line workflow, leading to longer lines and reduced efficiency. When cycle time is very short due to high demand, or when many dissimilar models are assembled on the same MM line, these problems become extremely significant. The current literature offers two main solutions for dealing with these problems. One is to open parallel workstations (Bhattacharjee and Sahu, 1986; Ghosh and Gagnon, 1989), and the other is to duplicate lines and divide the demands between them (Suer, 1998). Yet neither duplicating lines nor opening parallel stations necessarily solves these problems, since each line still assembles the same number of different models. Another alternative is to assemble the products on separate Single-Model (SM) lines, though the use of different SM lines can lead to long cycle times, resulting in a larger number of tasks at each station and thus reducing the advantages of using assembly lines.

Another improved approach is to assign models to different parallel lines. Each line assembles different models to achieve efficient and economical assembly operations. The effort in the current study was focused on the problem of designing such an assembly system, that is, on determining the division of models into lines. This problem is classified as a clustering problem, in which K models must be partitioned into M assembly lines and the lines must then be balanced so that workload variance between stations for the different models is minimized. Note at this stage that the problem deals with closed stations, which, in contrast to open stations, do not allow every model to exceed the cycle time.

The only researcher to consider this topic was Lehman in 1969 (Lehman, 1969). His objective in assigning models to lines was to minimize assembly costs, including balance delay, sequence delay and learning costs. According to his algorithm, models are assigned to lines using a greedy heuristic, under the constraints of required number of lines and limited line capacity. Another tool of Group Technology (GT) analysis was described by Burbidge (Burbidge, 1989). GT, however, offers classification techniques for production processes only and not for assembly processes.

2 Methodology

To solve the above problem, we have developed a Models Partitioning and Clustering Algorithm (MPCA), which establishes a smart partition of models into lines by first calculating the similarity between models based on their characteristics, and then clustering the models into lines based on their similarity. Prior to these two main steps, the problem data is initialized.

2.1 Initializing Problem Data

The input data is in the form of a precedence diagram that determines the precedence relations between the assembly tasks, an *m x n* task duration matrix that presents the task durations for all the models, where *m* is the number of models and *n* is the number of tasks, and a vector that represents the daily demands of the models.

1. **Creating Precedence Matrix P_{nxn}.** Matrix P transforms the precedence diagram into a matrix, such that if task i precedes task j, P_{ij} is marked with 1, and with 0 otherwise. In many practical problems, this matrix is given instead of the precedence diagram, so this step can be omitted.
2. **Creating Full Precedence Matrix P'_{nxn}.** Matrix P' presents all precedence relations, immediate and derived. This matrix is built iteratively from matrix P by adding to every task all precedence relations of its preceding tasks. The complexity of building a full precedence diagram out of the immediate precedence diagram is O(n+r), where n is the number of tasks and r is the number of arcs, representing the precedence relations.

2.2 Calculating Distance Matrix

In calculating the distance matrix, four variables are considered: precedence constraints, task durations, total work content and daily demands, which determine cycle times. Each of these four variables is analyzed independently, and finally a global distance matrix is built based on these analyses. This matrix contains values on a scale of [0,1], so that perfect similarity is ranked by distance 0 and perfect dissimilarity by distance 1.

Precedence Constraints

To calculate Precedence Constraint distances, the term 'Time window' is defined as the minimum and maximum of the possible execution time of a task, provided that all its precedence constraints have been fulfilled and no holdbacks and delays are caused. The time window of a task is determined solely by its preceding tasks and their durations. Calculating the overlapping percentage of the time windows determines the similarity between a pair of models. As the overlapping percentage grows bigger, the ability to balance the line successfully improves, as does the quality of the balance. The steps of this process are presented below.

1. **Calculating the Beginning Time of Time Windows.** The beginning of a time window is equal to the time needed to execute all the tasks preceding a specific task. Matrix L_{mxn} presents the beginning time of the time windows for all models. This matrix is shown in Equation 1.

$$L_{mxn} = A_{mxn} \cdot P'_{nxn} \tag{1}$$

2. **Calculating the Ending Time of Time Windows.** The ending point of a time window for a specific task is equal to the time needed to execute all the tasks which do not follow it. Matrix U_{mxn} presents the ending time of time windows for all models. This matrix is calculated in Equation 2.

$$U_{mxn} = T_{mx1} \cdot \overline{1}_{1xn} - A_{mxn} \cdot (P'_{nxn} + I_{nxn})^T \tag{2}$$

3. **Calculating Overlapping Percentages.** The distance between two time windows is determined as the overlapping percentage between them. This percentage is the proportion between the total overlapping time and the time period contains both time windows. Figure 1 presents the four elementary overlapping scenarios, and Equation 3 shows the relevant calculation for the overlapping percentage.

$$d = \frac{t_2 - t_3}{t_4 - t_1} \tag{3}$$

Note that the proportion ratio is equal to 1 when overlap is total (Full Overlap), and is negative when there is no overlap at all (No Cover). This last case indicates a clear mismatch between the models, since it clearly proves a certain delay from one model to the other.

This proportion is calculated between each pair of models and for every task, so that m(m-1)/2 vectors are generated, each with n cells.

4. Calculating Distances. This fourth and final step produces the distance matrix D^g. First, out of '*d*' values, calculated as presented in Step 3, the distance values are normalized to a scale of [0,1] by S=(1-*d*)/2. Then, the distance between a pair of models is calculated by applying the Euclidean Metric on the relevant S vector, as shown in Equation 4.

$$D_{ij}^{g} = \sqrt{\sum_{k=1}^{n} S_{ijk}^{2}} \Big/ n \tag{4}$$

Task Durations

Distances based on task durations are calculated by applying the Euclidean Metric on the differences between the task durations of each pair of models:

$$d_{ij}^{t} = \sqrt{\sum_{k} (t_{ki} - t_{kj})\, 2}$$

and normalizing the values to scale [0,1]. The results are then shown in a matrix defined as D^t.

Work Content

Distances based on work contents are determined by calculating the differences between the values of vector T. The results after normalization are shown in a matrix defined as D^{wc}.

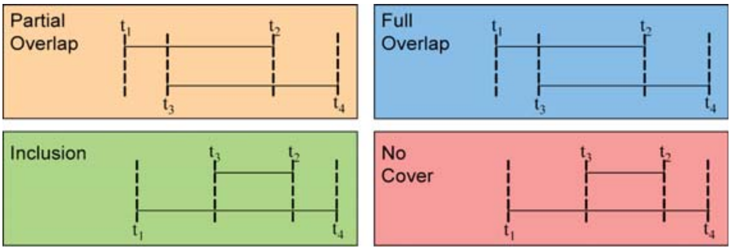

Fig. 1: Overlapping Scenarios

Daily Demand and Cycle Time

The last parameter considered is daily demand, which is proportional to the cycle time. This parameter is used in order to prevent line overload, thus shortening cycle times and damaging flexibility when balancing the lines. The distance, calculated in Equation 5, is determined by mathematical development of the differences between the boundaries of the optimal number of stations for each model:

$$d_{ij}^{n} = \frac{D_i + D_j}{\hat{T}} \cdot \left| T_i - T_j \right| \tag{5}$$

This process yields the distance matrix Dn.

Global Distance Matrix

The previous step results in four distance matrixes, each of which provides information about the differences between the models. These four matrices are combined into a single global matrix, to be used during the clustering process by calculating a weighted average for each of the corresponding values in the matrices, as shown in Equation 6.

$$D_{ij} = (1 - \omega_t - \omega_{wc} - \omega_n) \cdot \frac{b}{D_{ij}^{g}} + \omega_t \cdot \frac{b}{D_{ij}^{t}} \cdot D_{ij}^{t} + \omega_{wc} \cdot \frac{b}{D_{ij}^{wc}} \cdot D_{ij}^{wc} + \omega_n \cdot \frac{b}{D_{ij}^{n}} \cdot D_{ij}^{n} \tag{6}$$

The value of b is set as the minimal value of the averages of the distance matrices of D^g, D^t, D^{wc} and D^n. Note that this calculation is based on pre-established weights. Clearly, a different choice of weights results in different distances. Therefore, different sets of weights should be examined in order to choose the set that achieves the best solution. This step can be thought of as a supervision procedure in the Unsupervised Clustering problem. Although this may seem time consuming, it represents a significant advantage of the algorithm, that is, its generic character or its ability to deal with problems having different characteristics.

2.3 Clustering Models into Lines

Clustering is achieved using matrix D above and then applying an agglomerative hierarchal algorithm. Hierarchal methods are among the best heuristics for solving clustering problems with respect to method efficiency and solution quality (Duda et al., 2001). The clustering process starts with n clusters, each containing a single model, and continues by serially joining two clusters in each step, resulting in the smallest increase in the value of Related Variance Criteria, which defines distances between clusters (Equation 7). This distance criterion serves the goal of evaluating workload variation and increase in workflow fluctuation when the clusters are combined.

$$J_e = \frac{1}{2}\sum_{l_e}\sum_i\sum_j D_{ij}^2 / |l_e| \tag{7}$$

The growth in Related Variance Criteria as a result of joining together two clusters is equal to the addition to the relevant Between Groups Variance. Hence, the addition to J_e is equal to the sum of square distances between each pair of models of the two groups, as calculated in Equation 8.

$$\Delta J_e(A \cup B) = \sum_{i \in A}\sum_{j \in B} D_{ij}^2 \tag{8}$$

Dendrogram. The clustering procedure ends with the formation of a *dendrogram*, which presents the clustering process and the values of *Related Variance Criteria* in the form of a tree. The diagram shows which models should be assembled together in the same line (Fig. 2), where the first level matches the Single Model case and where the last level matches the pure Mixed-Model case. In between, at level k, there are (n-k+1) lines, among which the models are divided.

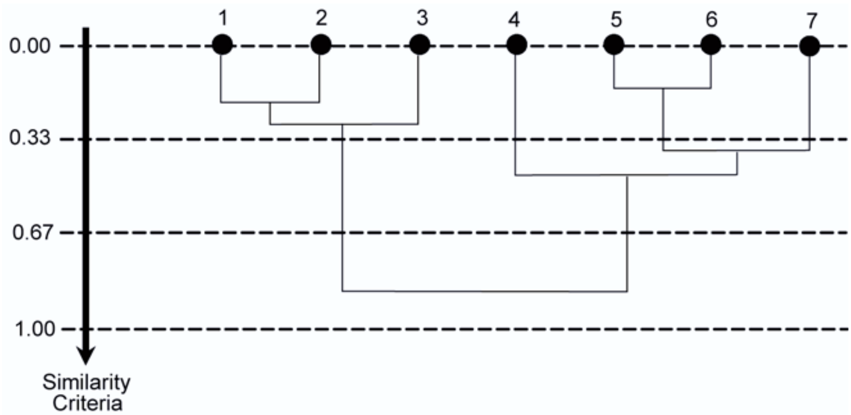

Fig. 2: Dendrogram

2.4 Assembly Line Balancing

Finally, for a closed and complete solution, an appropriate configuration of the assembly system must be chosen and the assembly tasks must be divided into stations. This is accomplished by balancing the lines obtained by the MPCA. In each step of the agglomerative hierarchal algorithm, each line is balanced using a line balancing algorithm. The total number of lines to be balanced in this process is (2m-1), because in each step only the line that has been clustered needs to be rebalanced. The configuration resulting in the minimal number of stations is chosen.

3 Conclusion

Assigning homogeneous models to parallel assembly lines can improve line efficiency and reduce assembly costs by dividing work more equally among stations, reducing work-flow fluctuations and increasing machinery and tool efficiency. Parallel lines can be thought of as an organizational approach for planning and designing an assembly system. Other organizational approaches include the Mixed-Model configuration, the Single-Model configuration and the Batch configuration. Table 1 compares all four approaches. Note that while the last three approaches involve a rigid planning methodology, the parallel lines approach offers a flexible method that examines different configurations of the assembly system and combines MM lines and SM lines in diverse forms, thus reaping the benefits of all the methods, especially MM and SM lines.

Clearly, the best way to plan an assembly system with parallel lines would be to evaluate all possible partitions by balancing all possible configurations. Yet, it is even clearer that this type of solution is impractical. For this reason, we have developed the Models Partitioning and Clustering Algorithm (MPCA) for clustering models to parallel lines. Basically, MPCA provides a good estimation of the similarity between models and presents a simple and clear view of the ability to balance models in the same line, as our empirical experiment proves. This empirical experiment to test MPCA performance was divided to four parts:

- Examining the performance of the algorithm’s two main parts, *Distance Calculation* and *Clustering Process*. The analysis results show an 80% success rate in classifying distance correctly, and a 90% success rate for the clustering procedure in finding the solution with minimal variance.
- Comparing MPCA performance to that of Lehman's algorithm clearly shows that MPCA completely outperforms Lehman's algorithm.
- Comparing to family configuration, which clusters models to lines according to family relations shows that MPCA performance was superior.
- Comparing to Mixed-Model configuration, in which all models are assembled on a single MM line, showed that MPCA manages to find a better solution than the optimal solution of classic Mixed-Model configuration.

Tab. 1: Organizational Methods – Comparison

	Advantages	**Disadvantages**
Parallel Lines	High efficiency Reduced inventories Moderate skill level for workers Flexibility in meeting demands	Complex production planning & control High primary investment
Mixed-Model Configuration	Reduced inventories No transfer costs between models Flexibility in meeting demands	Increased assembly complexity Workflow fluctuations Greater training time for workers Decreased tooling efficiency
Single-Model Configuration	Short transfer time (tasks) Increased equipment efficiency Low-level skills Improved learning	Inflexible and rigid system High attrition of workers due to limited occupation Vulnerable to faults
Batch Configuration	Simple production planning & control Increased equipment efficiency Reduced costs due to focus of resources and aim	High inventories Line changeovers costs Inflexibility in meeting changing customer demands

Although the last result is fairly trivial since every disjoint of a model from a MM line decreases the number of constraints in the problem, it is still very important since it proves that MPCA provides a platform to achieve better solutions than any Mixed-Model Assembly Line Balancing algorithm, optimal or heuristic. Thus, it is an important tool for optimally planning an assembly system that assembles several models.

4 Acknowledgment

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The Application of a Statistical Design of Experiment for Quantitative Analysis and Optimisation of Development Processes

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Abstract
Any current assessment of the process outputs, which are derived either by key figures or by process simulation, will not lead to process optimisation, because both the parameters' adjustment and the outputs' changes analysis are mostly done by considering only one factor at a time instead of considering the interaction between many possible interrelated factors. In order to improve this condition, this paper presents the application of a statistical design of experiment for analysing and optimising process outputs. The main objective of this method is to obtain outputs at or near desired targets and to minimise output variability by employing the desirability functions.

Keywords
Design of Experiment, Product Development Process, Process Analysis, Process Optimisation

1 Introduction

Many enterprises realise their necessities in optimising their development processes. This optimisation process is usually done by benchmarking their process' performances with the customer requirements in terms of four main components: (1) reducing the time to market and (2) reducing product costs, (3) improving the product quality and (4) improving innovation abilities. They have to assess their process outputs during the planning of the design process chain, because a success of this step will consequently translate into the success of the product development as a whole. Such assessment of process outputs requires the deployment of methods for generating figures as process outputs either taken from a dynamic process simulation or from a static method like key figures system [9].

Nevertheless having only both the static and dynamic methods is not adequate to optimise the outputs of the design processes. Both quantitative and qualitative analyses are needed to be employed in order to analyse the empirical data of design processes. The source of data for this exercise can be derived from either the experiments of real processes or the experiments of a process simulation. To date, the quantitative analysis of product development processes has been carried out only by superficial assessment without any well-planned experiments. Such assessment will not lead to process optimisation because both parameters' adjustment and analysis of outputs' changes are mostly done by considering only one factor instead of considering the interaction between many possible factors. By implementing this method, a process planer can not find the optimal setting of process parameters' combination. Furthermore, the optimisation is usually performed only for a single response and not for many responses. Additionally, this kind of analysis normally does not focus on the targeted adjustments of parameters for the improvement of outputs. This approach subsequently results in the increase of number of experiments which leads to the increase of time and money spent on the project.

In order to improve this condition, this paper presents the use of statistical design of experiment for analysing and optimising the development processes. In this context, the response surface methodology is being used in the form of a response surface design experiment for finding the optimal operating conditions for the simulation scenario. The main objective of this method is to obtain outputs at or near desired targets and to minimise output variability. For this purpose, the desirability functions are used to assess how close the responses are to their targets. In addition, the expected loss of the desirability function, which is derived from Taguchi loss function, is used to determine small variability. Finally, the sensitivity analysis is also performed for three reasons: (1) to validate the simulation model (2) to analyse the impacts given by the factors involved and their interactions within the responses and (3) to find the critical factors that can be utilised in setting the prioritisations to develop optimal strategies for optimising the processes.

2 Design of Experiments (DOE)

2.1 Introduction to DOE

According to the National Institute of Standards and Technology (NIST), the statistical Design of Experiments (DOE) can be defined as an efficient procedure in experiments planning so that the data obtained can be analysed to yield valid and objective conclusions [12]. In this context, one or more internal process factors are systematically alternated, so that the defined target on an optimal value can be achieved. There are several steps that have to be carried out when employing the DOE: (1) set the objectives and select the system variables, (2) chose the appropriate experimental design, (3) verify and validate the simulation model, (4) execute the selected experimental design, (5) analyse and interpret the simulation results.

Statistical design of experiment has been commonly used for optimising product and software design as well as product and process reliabilities in the industrial practices [5]. Unfortunately, its deployment for quantitative analysis and optimisation of product development processes is not as well known as it should be.

Nevertheless, in the context of product development processes, one DOE's implementation has already been carried out by Aas and Steen in order to optimise the processes in terms of the design quality [1]. Furthermore, it is very challenging to deploy the method of DOE in optimising the design processes in terms of the time to market and the design costs. For this purpose, a specific response surface design from the response surface methodology is used in designing the experiments.

2.2 Response Surface Methodology

Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques useful for analysing models which describe the behaviour of a response variable to a set of input variables, and following the goal of optimising this response [11]. Furthermore, RSM could also be applied to the simulated optimisation of multiple response variables by grid searching the responses to identify regions where overall performance was considered to be optimum [1].

In most optimisation problems, the function of the relationship between the response and the input variables is unknown. Thus, the essential step in

RSM is to find a suitable approximation for the function. The proper experimental design can be conducted here in order to collect the data and design the fitted response surfaces subsequently, so that the parameters in the approximation function can be estimated most effectively. By performing this, the RSM can determine the optimum operating conditions for the system or a region of the input space in which operating specifications are satisfied.

Basically, the response surface design can be divided into two categories: Box-Wilson central composite designs (CCD) and Box-Behnken designs. Due to the structure of the design experiments, the CCD has a better prediction capability than the Box-Behnken design. Unfortunately, the CCD requires more combinations of experiments. Therefore, the simplification of CCD is performed in the form of the central composite face centred design (CCF). For this reason, the CCF experiment design is deployed for fitting the response surface of the objective of the process optimisation.

2.3 Desirability Function

Defining the appropriate design experiment to fit the responses would not be sufficient to optimise the processes, if there are many objectives to be optimised.On the other hand, in the context of the optimisation of product development processes which consist of multiple objectives, it is quite impossible to simultaneously optimise all objectives due to the conflict that may occur among the objectives. Therefore, the engineer must make inevitably some trade-offs in order to find operating conditions that are satisfactory for all responses. For this purpose, the desirability function approach is commonly employed. This approach had been introduced by Harrington [6] and further developed by Derriger and Suich [4]. The desirability function is a scale measurement to determine how close a response value is to a target over a range of acceptable response values. In other words, a process with multiple objectives that has one of them outside of the target limits is completely unacceptable. Depending on whether a particular response is to be maximised, minimised, or assigned a target value, different desirability functions can be used. One-sided desirability function (for minimisation) can be defined as follows:

$$d(Y) = \begin{cases} 1, Y \le T \\ \left(\dfrac{Y-U}{T-U}\right)^r, T < Y < U \\ 0, Y \ge U. \end{cases} \tag{1}$$

If there are a number of responses, Y_1, Y_1,..., Y_q, each with respective desirability functions $d(Y_1)$, $d(Y_2)$,...,$d(Y_q)$, the overall desirability function for all of the responses can be defined as the geometric mean of the d_i that is :

$$D(Y_1,\ldots,Y_q) = [d(Y_1), d(Y_2),\ldots,d(Y_q)]^{1/q} \qquad (2)$$

If at least one of the responses is not within its acceptable region, then D = 0. If all Y's are exactly on their targets, then D = 1. Since the Y's are the functions of the inputs, the objective is to find the combinations of the levels of the inputs that maximise the value of D. Maximisation of D would be appropriate, if the inputs were not subject to random fluctuations.

2.4 Taguchi Loss Function

It has been described earlier that the maximisation of D would be appropriate, if the input factors did not fluctuate randomly. Unfortunately, the inputs for the stochastic simulation of product development processes fluctuate randomly, and this condition causes the actual responses to be random variables and the desirability will vary randomly. In order to reduce the variance of the responses, Taguchi introduces a loss function method that expresses the loss incurred by a random variable taking a specific value [2]. Here, the loss is described as a function of the distance between a random variable of desirability and a fixed specified target value d(Y) = 1 [14]:

$$L(D \mid x) = (D-1)^2 \qquad (3)$$

The expected or average value of the desirability loss function at a specific nominal point x is [13]:

$$E(L(D \mid x)) = \int_0^1 (D-1)^2 f(D \mid x)dD = (\mu_D(x)-1)^2 + \delta^2(x) \qquad (4)$$
$$= DEL(x)$$

The objective is to find the value of x which minimises the Desirability Expected Loss, DEL (x). In minimising the DEL (x), μ_D (x) has to be close to 1 and μ_D^2 (x) has to be small. The yield at a nominal point x can be seen as the probability that all responses are in regions of acceptable values [3]. In other word, the overall desirability D_0 = 1 if all Y_i are acceptable and D_0 = 0 otherwise (in this case, the exponents s or r in the individual desirability functions have to be set to 0). Then,

$$E(D_0 \mid x) = \mu_{D_0}(x) = f(D_0 = 1 \mid x) = y(x),$$
$$DEL_0(x) = (\mu_{D_0}(x) - 1)^2 + \sigma^2_{D_0}(x) =$$
$$(y(x) - 1)^2 + y(x)(1 - y(x)) = 1 - y(x) \quad (5)$$

Thus maximizing μ_{D_0} (x) or minimising DEL_0 (x) produces an equivalent result in maximising the yield value of y(x).

3 Process Analysis and Optimisation

3.1 Optimisation Strategy

The methodologies of the design of experiment described in chapter DOE are applied in order to optimise the development processes of *automated air conditioning trainer system*. According to the design of experiment methodology explained earlier, the optimisation strategy begins with setting up the objectives of the process. In general, the objectives are to optimise the product development processes by minimizing the time and cost associated with the development process. Following that, the essential input variables as well as the adjustment levels are determined in order to achieve the targeted responses. The input variables are the process structure, the iteration probabilities of development activity, the process time of development activity, and the number of resources where three adjustment levels are set for each input variable. Based on this information, the CCF experiment design is selected. To simulate the model, the modelling and simulation tool *DimSiMP (Distributed Modeling and Simulation of Mechatronical Product Development Processes)* is used [10]. After the simulation model is verified and validated, the selected design experiments are carried out in the simulation model. Finally, the simulation results are analysed in term of their sensitivities with the help of the statistic software *JMP* from the firm *SAS* [8]. Based on the analysis done the optimum conditions of the process are retrieved.

The experiments or scenarios can be easily built in the simulation model by means of the simulation system *DimSiMP* where each model element can be set as a factor with a certain adjustment level. These factors can directly manage the adjustment levels in the simulation model. For this purpose, there are 27 scenarios consisting of 3 experiments representing the centre points, 4 parameters and 3 levels for each parameter. Corresponding to the appropriate confidence interval, each scenario is simulated in 300 cycles and results in mean value and standard deviation for the total development time, the development costs as well as the desirability value.

After the target value of the development time and costs as well as the upper limit of both responses are set, the results show that scenario with the pattern: ++++, which implies that its factor lead time has the level of +1, the factor iteration probabilities has the level of +1, the factor resource number has the level of +1 and the factor process structure has the level of +1), gives the optimal results in terms of the total desirability value for the exponent of the desirability function r = 0.

The total desirability value D(time, cos t) for this scenario results in 0.8. This result also means that 80% of the response values of this scenario can achieve the target value of both the development time and cost with the variance of the development time for 5 days and of the development costs for 15000 Euros. By adjusting the upper limit of both responses, the developer can find that the operating conditions in the scenario with the pattern: ++++ are robust for any number of variances.

3.2 Sensitivity Analysis

In the context of sensitivity analysis, the simulation model is first assessed whether the model is reasonable or not. Table 1 shows the variance analysis results which compare the variability of the predicted model with the error.

Tab. 1: Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	14	1.7201860	0.122870	29.8007
Error	12	0.0494769	0.004123	Prob > F
C. Total	26	1.7696630		< 0.0001

DF Degree of Freedom, *Sum of Squares* the variability measured in the response, *Mean Square* a sum of squares divided by its associated DF. From this table it can be seen that the *F*-ratio is bigger than the mean square which indicates that there is a significant effect in the model. Furthermore, the probability of the greater *F*-ratio (Prob > F) is significantly less than the probability of significant level (α = 0,05) which means that the hypothesis that all the regression parameters are not significant is not true. This value is a sound base of argument to say that the model is reasonable and valid, and it has at least one significant regression factor in the model. The model's goodness of fit is further confirmed by its high R-square of 0.97 and high R-square adjusted of 0.93.

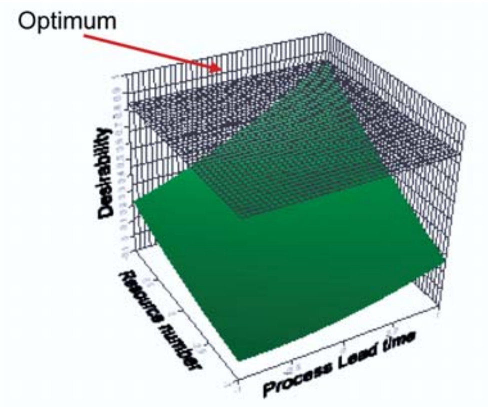

Fig. 1: Surface Profiler for the Desirability Value

This numbers denote that the amount of reduction in the variability of response obtained by using regressor variables is about 97 % and it is about 93 %, if it takes the number of regressor variables into account. Furthermore, the sensitivity analysis is carried out in order to assess which input variables are the important factors in affecting the variability of each response as well as the overall desirability function. Additionally, this information is also useful in understanding which inputs are the limiting factors in the response variability and which efforts should be carried out in reducing the variability. By carrying out the *t*-test which compares the estimate value of each factor with its associated standard deviation to result in the *t*-ratio, the significant factors can be determined. Those are the process lead time, the resource number and the interaction between both factors. They have significant high values of *t*-ratio. They also have significant less probability of getting greater *t*-ratio than 0.05 (probability of significant level) which means rejecting the hypothesis that the parameter is not significant in the model. After several analyses are carried out for validating the model, the modeller can interpret the model by plotting the response surface for respective objective. Fig. 1 presents that the optimal value of desirability can be achieved by adjusting the resource number to +1 and the process lead time to +1.

4 Summary and Acknowledgements

The paper presents the application of statistical design of experiment (DOE) in the simulation project methodology in order to optimise the product development processes. For this purpose, the CCF (central composite design face centred) from the response surface design is applied to fit the response values in terms of the time to market and the design costs. Due to the possible goal conflicts in the product development processes, a trade-off is carried out by deploying the desirability function. The desirability function simultaneously optimises the time to market and the design costs by measuring how close both response values are to a target over a range of acceptable response values. In combination with the Taguchi loss function, a modeller can determine the desirability expected loss value of each deviation of the response values from the target value. By determining the desirability expected loss, a modeller can find which simulation scenario or operating conditions that can satisfy the target value of both responses simultaneously. Subsequently, the sensitivity analyses are conducted to validate the simulation model and to recognise the significant factors of the model. For the case example, the methodologies are applied to optimise the product development processes of the automated air conditioning trainer system. The results of the process optimisation have been recommended to be implemented to the real processes at one Mechatronic Company in Indonesia.

In the context of the distributed development processes, the methodologies can also be applied to each development partner. Each partner can achieve the optimisation of his development processes and integrate its optimal conditions in the whole development processes as specified in the supply contract [7], so that the total optimisation of product development processes can be achieved.

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PLM Services in Practice

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Abstract
The paper presents recent developments in product data modelling technology and their application in integration products for composing valuable software assets in dynamically adopting workflow systems. The findings are accompanied by an evaluation of dissemination results within a business critical OEM-supplier relationship scenario realized with best of breed software components – IBM Process Server and PROSTEP OpenPDM integration suite.

Keywords
Business Process Modelling, Product Data Management, Product Lifecycle Management, Service Oriented Architecture

1 Introduction

The long term success of the manufacturing industry depends on its ability to reduce development cycles and development costs by sharing expensive engineering capabilities, streamlining processes, avoiding time consuming replications of work steps and forming dynamically cost efficient collaborations to design fast and efficiently more and multiple products. The ability of the original equipment manufacturer (OEM) to form strategic partnerships with selected and specialized system developers, to share the development risks with a shrinking number of partners and to reduce the number of development cycles with second- and third-tier suppliers at the same time becomes a crucial success factor. To fulfill those requirements a suitable IT infrastructure, e.g. development process supported by highly flexible IT services are necessary. But it is essential, to build such solutions on open and standardized IT systems to safeguard investments and to ensure a return of invest in the lifespan of the definition of those processes which outnumbers the lifespan of both hardware and software components. This requires the alignment of the IT services with the development processes themselves instead of implementing isolated software systems. This becomes most effective if IT drives the development of business processes. One approach to meet this challenge is the implementation of a Service Oriented Architecture (SOA). A SOA realizes a strategic vision of an enterprise by orchestrating business processes mapped to potentially standardized services and components. Essential artefacts of a SOA are services, service repository and a enterprise service bus.

The paper presents an approach based on standardized components to build and orchestrate services in a SOA to fulfil requirements of distributed product development scenarios.

2 OMG PLM Services

The standard OMG PLM Services [8] is a ProSTEP iViP working result and is standardized by the Object Management Group (OMG). It is the first standard comprising current XML and Web Services technologies with a STEP data model – thus providing both syntax and semantics in one standard specification. The latest version of this standard is compliant to the data model of Conformance Class 21 of the 3rd maintenance version of STEP AP214 [3]. It encourages the re-use of WebServices standards like WS Security and WS Addressing.

OMG PLM Services have proven strong functional capabilities which support cross-domain, cross-system and cross-technology collaboration. As a comprehensive framework they are based on the OMG Model Driven Architecture (MDA) [6]. Therefore, they are not restricted to WebServices implementation but allow by design interoperable implementations on different platforms and with different programming paradigms.

OMG PLM Services provide a solid foundation for collaborative engineering scenarios like browsing in distributed product data structures, design in context, product data visualization, and others. Their latest version is extended to support message oriented communication patterns and to realize Engineering Change Management scenarios according to the ECR VDA recommendation [11].

Unique about OMG PLM Services is that they support industry-related use cases by defining both the informational and operational process-related aspects as defined in [4].

The informational viewpoint is structured according to the units of functionality of the original STEP AP214 specified in EXPRESS [2] but mapped to UML [10] by STEP part 25 mapping from EXPRESS to XMI. The units of functionality in the original STEP application protocol comprise unique partial sets of the defined data model. Combinations of units of functionality and applied restrictions expressed in OCL form the so-called conformance classes. Conformance classes capture domain relevant information like product structure, configuration and change management. They map easily to data model sets to realize use cases defined in the OMG PLM services specification.

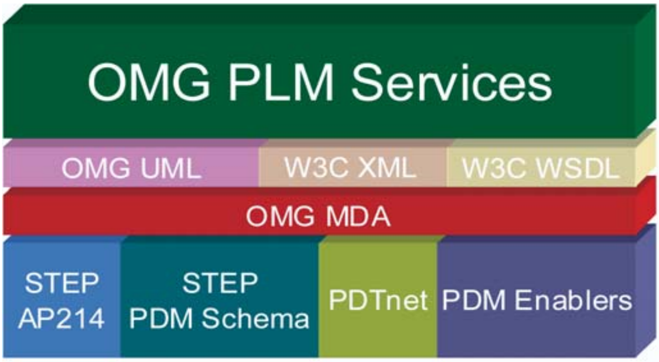

Fig. 1: PLMServices – A standard based on standards

The operational viewpoint defines a set of carefully chosen functions and their impact on instances of subsets of the informational model. The functions are as well the result of a requirement analysis and fulfil documented use cases. The use cases realize requirements from the chosen aspects of the product data management of the product lifecycle. Therefore, the specification goes beyond a pure interface definition, and identifies building blocks to construct relevant work packages. The building blocks are organized in layered conformance points of the computational viewpoint.

Based on a generic queries conformance point specialized queries for specific elements of the informational viewpoint allow a very fine grain, object based control of information flow. This is the domain of object oriented approaches. A more general point of view to support service oriented approaches is defined in the PDTnet and the Engineering Change Management conformance point which map functions directly to use cases as defined in both domains, PDTnet [7] and ECM [11], respectively.

PLM Services is a standard based on standards (see Fig. 1), and combines the modelling capabilities of the object oriented approaches (PDM Enablers) with the use case driven approaches (PDTnet) and the data modelling approaches (STEP AP214 and PDM Schema [9]). With the model driven architecture of the OMG interoperable implementations supporting WebServices and document related scenarios are paralleled by more conventional approaches with programming language paradigms, e.g. Corba [1] bindings, JAVA implementations etc.

3 Technical Solution

3.1 Integration and Service Oriented Architectures

Integration in a service oriented architecture (SOA) is characterized by three main architectural constructs: a common data model; a common invocation model; and service choreography. The common data model refers to the consistent use of attributes and methods to describe objects that will be exchanged. The common invocation model refers to how objects will be imported and exported. And service choreography refers to how multiple services are orchestrated into business processes. In support of these constructs are services that simplify integration such as data mapping and translation.

IBM's WebSphere Process Server (WPS) middleware provides the environment that supports all of the above. Of particular interest is a common standard data model, which can be tailored for specific integration requirements. As an example, when integrating PDM applications, the standard data model would support a data superset of the implemented proprietary solution, including all attributes necessary for each of the applications. From this superset, generic business objects (GBOs) are created. The data model and the associated GBOs are re-usable, and over time, could serve as a standard for integrating the PDM applications.

The service choreography construct orchestrates the order in which services are invoked. In the case of WPS, these processes are defined using Business Process Execution Language (BPEL) [5]. As the BPEL executes, a specific request for a service is sent through a connector to or from an application. The service takes the form of a request that either delivers a business object to the application ("write to" function) or receives a business object from the application ("read from" function) for delivery to another application.

In the case of PDM applications, a typical request would be to CreatePart, UpdatePart or ReleasePart. Requests realized as services access one or multiple data sources and modify PLM data according to the semantics defined in the use case and corresponding PLM services functions. The business rules of the underlying PLM systems must be utilized such that the specified semantics if the PLM Services functions is realized. This requires the customization to the data model mapping, in general or specialized for the chosen method.

The application context of a process server provides quality of services like security, transaction, fail-over, load balancing, and so on. Once a process is modeled in BPEL and instrumented, it represents a service in its own, and it can be re-used. A hierarchy of services may be orchestrated by flows and micro-flows.

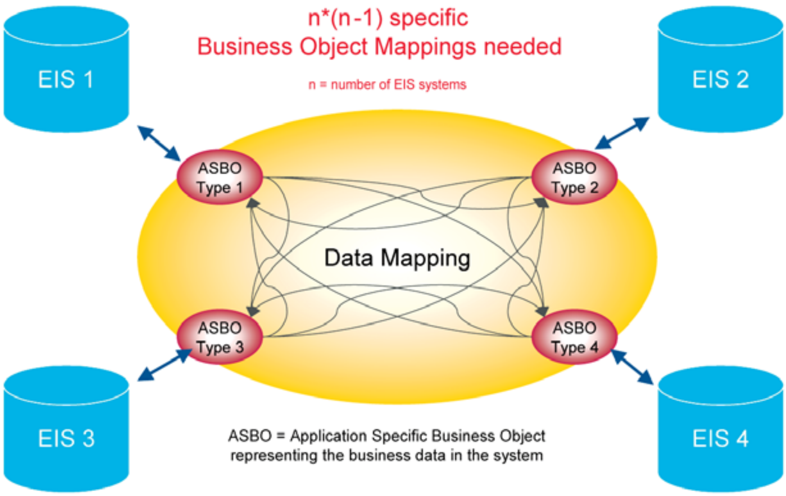

Fig. 2: Cost-intensive EIS Integration with Application Specific Business Objects

3.2 Handling of Application Specific Business Objects

Typically when integrating different PDM applications, the interfaces of these systems are different and do not match. Different application specific business objects (ASBOs) represent the data in the systems. To share data between the systems, a solution can be to provide data mappings from and to the ASBOs of all involved systems (see Fig. 2), essentially creating multiple point-to-point integrations. This way is very cost-intensive, especially when integrating new applications where mappings have to be provided to and from all other applications. The number of point-to-point integrations explodes with the addition of new applications.

In contrast to this approach, it would be highly beneficial to provide one data superset to which the ASBO's could be mapped, eliminating the need for point-to-point integration. Such a superset would be provided by a Generic Business Object (GBO). With a GBO approach the need for costly point-to-point mappings is eliminated and the integration scenario becomes scalable and manageable.

3.3 PROSTEP OpenPDM and SOA Integration

In the context of PDM integration, considerable time and effort could be saved if the three SOA architectural constructs were available in advance of the integration. If a standardized data model existed that provided the data superset necessary to create the GBO's for all PDM applications, then little additional effort would be required to identify and create this superset. If a standardized invocation model existed for the most commonly used PDM applications, then little additional effort would be required to identify and acquire the connectors. Furthermore, it would be incumbent upon the provider to ensure the completeness and efficiency of the connectors, both to the latest versions of the PDM applications and to the data superset. And lastly, if a set of standardized set of business process models existed, then little additional effort would be required to apply and tailor these models rather than creating them from "scratch".

OpenPDM provides two of these constructs for SOA integration of PDM applications: the components for the invocation, namely the PDM connectors in conjunction with OMG PLM Services queries; and the standardized data model, the OMG PLM Services schema. The OpenPDM product mediates between the GBO and the ASBO and maps generalized functionality of the OMG PLM services standard conformant interface to corresponding suitable proprietary internal API functions.

Interesting enough, the GBO approach allows generalized process orchestration as well. The overall architecture with one or multiple PDM data sources integrated is illustrated in Fig. 3. The process may be modeled independently from the underlying custom PDM model. This allows seamless replacement of data sources with continuing process support or – even more beneficial for the enterprise – optimization of the business processes as a result of monitoring and hot spot identification without change to the data backbone. The processes become a separately manageable asset as part of a SOA.

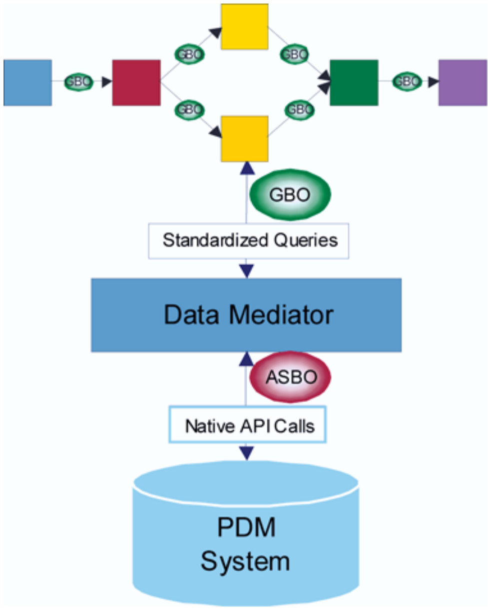

Fig. 3: Data mediation for integrating a PDM system into a business process

4 General Cost Comparison

4.1 Cost of Developing and Maintaining Connectors

One of the basic concepts is that of the standard backend system connectors. For each relevant PDM system on the market, a standard connector is provided by the OpenPDM solution suite.

If an enterprise were to have implemented the off-the-shelf standard connectors for a number of backend systems, the enterprise would have experienced the following:

- Effort for provision of base connectivity to WPS – no effort
- Effort for customization to its environment –
  some person days total per backend
- Annual effort for maintenance and new versions – no person days.
- Additionally, the risk of delivery time delays, partial functional non-fulfillment and budget overspend would have to be taken by the enterprise.

If the enterprise were to have created these connectors from scratch, it would have experienced the following:

- Effort for from-scratch-development of specific connector (performed by well-skilled, specifically experienced staff) into a SOA – significant number person months per backend system minimum
- Significant annual effort for maintenance and new versions.

Standard PDM connectors are maintained as products. An independent software vendor (ISV) provides full maintenance for the standard PDM connectors. In case of new PDM application releases, the PDM connectors are reworked and optimized for the new release.

It is interesting to note that the effort invested by the ISV in the development of its standard PDM connectors for resale depends on the backend systems, but typically involves some months of effort. This includes analysis, concept, implementation and quality assurance.

In the case of using WPS alone, the connectors would either be provided by the ISV's themselves or third party vendors, or developed from scratch. Not all ISV's provide connectors, and for those that do, the synchronization of connectors to product release cycles is problematic. Developing a connector from scratch typically requires one or more man-years of effort plus additional effort for testing.

4.2 Cost of Developing and Maintaining Non-standard Data Formats

In solutions built on WPS, a facility that generates GBO is needed. A standard connector based SOA provides this facility with its PDM connectors. Due to the comprehensive approach that is the basis for the OMG PLM Services, virtually all kinds of PDM data can be represented by entities in the OMG PLM Services schema. This has been proved in a large number of projects using PLM Services and, in more generality, in an even larger number of projects based on the equivalent STEP AP214 data model.

In case of an implementation without standard based connectors, this GBO layer has to be implemented from scratch. A data model for the GBOs has to be planned, verified, and to be implemented. Experience shows that this conceptual work takes great effort and needs highly-specialized people who are able to survey all the requirements that are caused by a PDM integration project.

4.3 Cost of Implementation

The efforts to spend in case of the COTS based implementation based on WebSphere Process Server and OpenPDM are:

- Installation and customizing of WebSphere Process Server and standard PDM connectors
- Implementation of BPEL processes
- Customization of OpenPDM mappings to the proprietary data models
- Testing

An implementation based on classic WebSphere Process Server and hand-made access to the backend PDM systems would cause the following efforts:

- Installation and customizing of WebSphere Process Server
- Implementation of PDM backend access modules
- Implementation of mapping tools for each PDM backend module
- Creation of mapping scripts between each of the PDM backend modules
- Implementation of the business process using J2EE
- Testing

5 Conclusion

The utilization of a set of predefined standard PDM connectors reduces drastically the cost of ownership and time to market for a typical integration scenario in a heterogeneous environment. WebSphere Process Server and OpenPDM together form a basic solution platform for a SOA targeting at the resolution of PLM problems. Their openness and scalability together with the quality of services provided by the standard J2EE application platform in development, and even more important, in operation and management are essential features to guarantee the success of an integration and migration project.

6 Disclaimer

The following companies have contributed substantially in the OMG PLM Services standardization: Avanion (Software Consultant), BMW (OEM), Bosch (Supplier), Conti Temic (Supplier), Daimler Chrysler (OEM), Keiper (Supplier), IBM (Software Vendor), in-GmbH (Software Vendor), Magna-Steyr (Supplier), PartMaster (Software-Vendor), PDTec (Software-Vendor), proficiency (Software Vendor), ProSTEP/iViP association (administration, sponsoring and networking), PROSTEP (Software-Vendor), SAP (Software vendor), Scania (OEM), T-Systems (Software-Vendor), UGS (Software Vendor), Valtech (Software Consultant), Volkswagen (OEM).

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Composite Applications Enabling Product Data Management Applying SOA Principles and Software Factory Methods

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Abstract
In the early design phases of a product, the product features are defined according to their functional specification. Changes in the design process will provoke tremendous costs which will increase during the ongoing development process. Surveying and evaluating the product attributes as early as possible will not only save costly changes, it will help to improve the product quality right from the beginning. This paper describes the development of composite applications for the company-wide management of product data during the whole product life-cycle applying the SOA principles. Furthermore this paper points out, how SOA principles contribute to the factorization of the software development process.

Keywords
Service oriented architecture, product data processing, product development

1 Introduction

Service oriented architecture can be defined as a software architecture that defines the use of loosely coupled, independent services to support the requirements of the software users. The SOA environment replaces the monolithic software systems by enabling resources in a network not depending on the underlying platform implementation. SOA also aims at the support of complex business processes. SOA is often based on web service standards like SOAP, WSDL or also CORBA or also Enterprise Java Beans, but SOA should be regarded as technology independent.

In March 2006, the OMG SOA Special Interest Group adopted this definition for SOA [1]: Service Oriented Architecture is an architectural style for a community of providers and consumers of services to achieve mutual value, that

- Allows participants in the communities to work together with minimal co-dependence or technology dependence
- Allows a variety of technologies to used to facilitate interactions within the community
- Specifies the contracts to which organizations, people and technologies must adhere in order to participate in the community Provides for business value and business processes to be realized by the community

SOA aims at the combination and coupling of services of different abstraction levels to achieve high value functionality. The services can be defined as reusable artifacts, providing added value [2]. A service comprises the technical content representing the business process, which provides the software user an efficient support doing his job. The specification of the services can be mapped on the adequate technology, mostly applying UML. This description can be mapped on technologies as web services or CORBA. The technical content can be analyzed by the application of tools like ARIS applying use cases, activity diagrams and sequences of business processes as well as the modeling of dependencies of data. Furthermore this technical content can be enhanced with roles and rights concepts as well as transaction mechanisms which are mapped on technical frameworks and protocols.

Therefore SOA is suitable for Enterprise Integration Application projects, mapping a platform independent model on a target platform like a web application server (Java EE platforms) and tools for data management. These aim at the encapsulation of persistent data to guarantee a high flexibility and to avoid redundancies. The high flexibility, modularity and the orientation towards the business processes represented by the service is achieved with a higher implementation effort of the business logic of the services in the beginning.

As in companies a heterogeneous software landscape is existing, a new integration level can be achieved by building packaged composite applications covering the user's needs, applying SOA for the integration. A composite application can be regarded as a collection of existing and independently developed applications provided with a new business logic. Brought together, it can be perfectly aligned to a business process.

2 Building up Services

2.1 General Requirements

When new applications are developed, today decisions are more influenced by the aspect of integration. Building a new software applying modern tools and methods is not enough, as there are lacks in the provision of a continuous data flow, data access for a highly linked user group with differentiated views on the information. Therefore the decisions for software architectures are influenced and driven by concerns like re-usability, serviceability and the degree of integration. The analysis of the business process for weight tracing and monitoring showed, that it is not sufficient only to calculate different weights like actual weight, target weight or the overall weight of a vehicle like a passenger car, truck or aircraft, much more information and data has to be managed. Beside of the weights, relevant information about the product like the product structure, various configurations of the product and the related information about the responsible contact persons in numerous development departments had to be taken into concern. Furthermore, some of this information is already available in third party systems and legacy systems like PDM systems and has to be imported. Another requirement for the availability of the data was the provision of defined interfaces. To enable this transparency, it is agreed to refer to standardized tools and methods.

2.2 Analysis of the Business Process

The business process was analyzed applying the event-driven-process chain (EPC), a method provided by ARIS. The EPC is an ordered graph of events and functions, in which as a result, all relevant data, data flows, third party and legacy systems as well as the dependencies have been retrieved. Furthermore all relevant organizational information like contact persons, departments involved in the product development process have been detected and documented which will be later on reflected in a rights and rolls concept. The analysis of all stakeholders is extremely important to get an accepted overview and definition of all responsibilities. The product information comprises all weight data related to the product structure and single parts of the product. The product structure can be related to the organizational data, which is not limited to the departments of a brand, it can also comprise the whole company as well competitors.

A detailed description of the business process and the process steps depending on internal and external events is provided by use cases, activity diagrams and sequences as well as the data, structured in a data model. These descriptions serve also as functional requirements of the application and will be combined and enhanced with technical information like transaction behaviour, rights and roles concepts, and constraints. Furthermore a detailed description of the graphical user interface was built up to achieve an optimized support of the working process and efficient support of the users. The analysis of the business process leads to the identification of other services which are necessary and at the same time to the specification of the requirements of these services. Furthermore a detailed description of the graphical user interface was built up to achieve an optimized support of the working process and efficient support of the users.

2.3 Psychological Aspects of Software Projects

The analysis of the business process and the intensive dialogues with all departments involved, revealed the psychological component of this IT topic: the working process will be changed, the staff has to change from the old, used methods to a new working method, which creates more transparency concerning results and clearly defined responsibilities. The analysis of the actual business process and the creation and definition has to be done together with the end users to achieve an agreed process and accepted responsibilities. This can be carried out defining use cases, activity diagrams and GUI-prototypes. The end-users have to restore themselves and their working content in the new application. Furthermore the creation of a GUI prototype has two major impacts: it helps to illustrate to future working process and to discuss it. In addition, the identification and acceptance of the end-users with the software project will increase as soon as they are involved in the design of the user interface. On the implementers side, it helps to have a defined specification agreed with the customer and end-user respectively. The psychological component is often neglected in IT projects, but the impact of changes in the working process as well as new responsibilities between all stakeholders needs intensive reflection. Furthermore, each department now contributes its service to this architecture, the software system is no longer limited as a specific tool, it is joining one IT infrastructure and structured information which has to be provided company-wide. Like this, the new application does not only combines and replaces a few old solutions, it will be more: an integrated platform for several services.

3 Implementation of the Weight Tracing Service

On the realization level the platform independent model can be transformed to the target platform (like Java EE or .NET). Beside of OpenSource application server projects like JBoss or GlassFish, several integration platforms are already available like SAP's NetWeaver, Bea's WebLogic or as chosen in this case, the implementation was based on IBM WebSphere. The lowest layer of a SOA component are the data services, the data base applied is Oracle 10i. The persistence and the O/R mapping of the data access objects is assured applying Hibernate as persistence framework. Referring to the architecture of a J2EE server, the business logic and all beans like session bean and message-driven-bean are part of the EJB container. The client can access the EJB container either via the home interface and the JNDI-service or the remote interface as shown in figure 1. The GUIs of the client have been designed together with the end-user to support their work and process to a high extend.

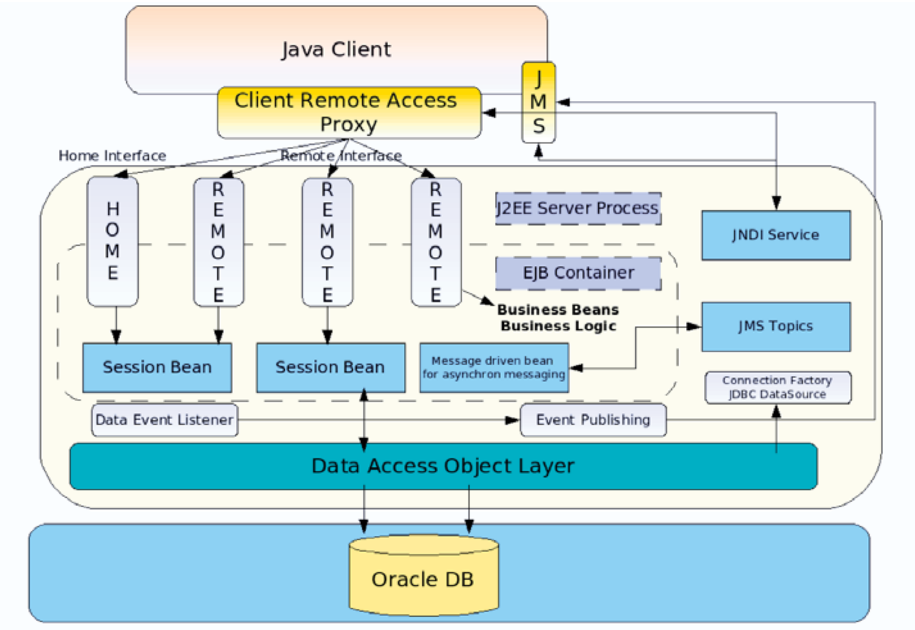

Fig. 1: Architecture of the weight monitoring system in compliance with SOA principles

The weight tracing application allows different users to create, edit and delete information concerning vehicle weights depending on their rights and rolls. Weights can be either retrieved from legacy systems or they can be edited by users according to their responsibilities and affiliation to an organizational unit. The origin of the weight information can be either the real weight of existing parts, a target weight which shall be achieved or a calculated weight, which is provided by the CAD system.

The weight information can be calculated and compared for different vehicle variants as well as different power-train variants. Vehicle variants can be coupé, sedan or station wagon for the automotive branch, the service can comprise different layouts of aircraft like passenger, passenger and cargo combined or cargo for the aerospace application respectively. Like this, at an early stage of the design the influence of additional technical equipment on the overall weight and the center of gravity can be examined. Weights can be calculated following assemblies and structured information like various cabin layouts of an aircraft. During the development process, the resulting weight calculations will get more and more exact, missing data can be completed using the knowledge gathered in the development of other type series. Furthermore, the controlling of the weight information allows to take actions at an early stage. These actions can be proposals to change positions or material of components or others to reduce the weight of parts and assemblies. The changes of material or even the position of parts and assemblies can implicate a change of costs for example due to a more complex and time consuming assembly. These costs have also to be taken into concern as early as possible.

The structured information of all brands within a company, the type series and all belonging vehicle variants allows also to take advantage of design solutions already made and to reduce the number of variants and to increase the number of parts already used in other vehicle projects. Experiences to solve problems within different type series can be transferred and parts can be exchanged between type series even if they belong to different brands. The structure is shown in figure 2. Another service accessing the data model is e.g. a report system, which creates standard reports for management summaries to give an overview of the actual state of the vehicle development or services managing costs. Furthermore services for the management of the weight information will use the data base in order to predict product attributes as fuel consumption as early as possible.

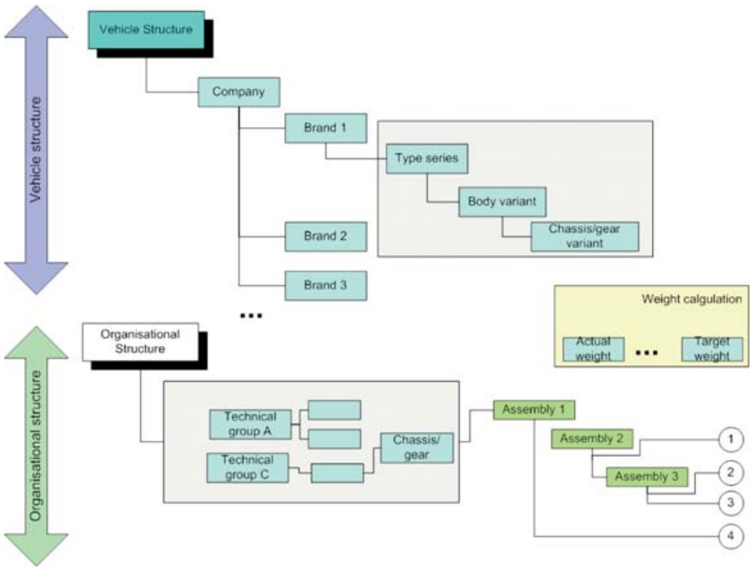

Fig. 2: Structure of vehicle and organizational information

4 The Contribution of SOA to a Software Factory

The industrialized software development is reflected by the application of standards and principles of SOA: developing software is no longer limited to small teams or individuals, there is an ongoing change towards manufacturing, reusing components created by a large number of suppliers. The processes, designs are standardized, using languages, frameworks and tools to automate the software life cycle [3]. Modern development methods aim at an optimization of change and not complexity, providing reusable content and patterns. Nowadays, software is no longer an individual product, but a component of everyday life [4]. Software factories are development environments configured to support the rapid development of a specific type of application. They will automate the packaging and delivery of the reusable assets, including models and models driven tools also comprising templates and utilities, development processes and implementation components, patterns, configuration and documentation. As SOA aims at the reusability of modular services, integrated in a standardized environment, SOA enables the tayloristic and rapid implementation of new services. The implementation will be supported by a large number of software suppliers, like in industrial processes of manufacturing industries as the automotive industry.

The implementation of software in distributed companies and the realization of offshore projects are enabled, providing new cost advantages. The focus is moving to the tasks architecture, design and consulting, which requires a high understanding of the application itself as well as a profound knowledge of the business processes.

5 Conclusion

The paper shows the benefits of the application which has been realized for a service oriented architecture. The careful and profound examination and analysis of the business process leads to an agreed procedure for the work process, responsibilities, the implementation and acceptance of the software. The business process was transformed from an isolated process into a shared service which is easy to maintain and which is available for all users. Future integration of other services or legacy systems can be achieved at lower costs, avoiding the complexity of point-to-point integrations. The database can be used by other services and other departments, creating new views on the data, according to their rights and rolls. All relevant data is now available for all users and contact persons of the development departments during the whole product development process. Actions in the development process can be taken at an early stage which will avoid tremendous costs for changes in the late design process. Furthermore, the application of standards and standardized software architectures enables the rapid development of new services, which is similar to the production processes of the manufacturing industry.

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A Holistic, Methodical Approach to Evaluate the PDMS-capability of Companies

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Abstract
The implementation of a cost-intensive Product Data Management System (PDMS) often fails because of false expectations within the companies and inadequate preconditions. Regarding the current enterprise capability for the deployment of PDMS, the need for a methodical evaluation occurs. This PDMS-capability is determined by specific PDMS-influencing parameters and can be categorized into several grades of maturity. The evaluation itself is conducted using the so called Capability Scorecard (CSC). The CSC is a potent tool which marks company specific weak points of a PDMS-implementation to systematically launch improvement procedures. The methodical approach for rating enterprises concerning their PDMS-capability as well as the CSC is content of this paper.

Keywords
Product Data Management System (PDMS), PDMS-capability, PDMS-maturity, Capability Scorecard (CSC)

1 Introduction

Many companies are evaluating the usability and potentials of Product Data Management Systems (PDMS) within a Product Lifecycle Management (PLM) strategy. With the strategic and company-wide use of product data new products should be brought onto the market more quickly and cheaper. Also, innovations have to be enabled and the value-added chain from the supplier to the customer should be formed as efficient as possible. Above that, an efficient, real time knowledge management has to be supported in a development project environment, which is becoming increasingly cooperative and virtual. An integrative solution for these topics is the usage of the PDM technology. The main question is whether or not a company is fit enough for the efficient usage of a PDMS at the time of its introduction and afterwards.

Therefore, a measurement system is necessary. By this, the current state of a company's PDMS-capability can be checked continuously and compared to the desired state on a strategic and an operative level. Room for improvement can be identified and specific improvement measures can be derived. By this procedure the basis is set for a continuous PDMS controlling which creates a permanent increase of efficiency.

Today, such a holistic approach for industrial application does not exist. This gap can be filled by the concept described in this paper.

2 Requirements and Definitions

The following requirements for a PDMS-implemenation are mostly identified among companies (VDI2219, 2002; Saaksvuori, 2004; Stark, 2006; Feldhusen and Gebhardt, 2005b):

- an explicit consideration of strategic and operational business objectives aspired by introducing a PDMS;
- a methodical proceeding regardless the system itself, providing concrete instructions for each phase of the project;
- a proceeding for evaluating the current PDMS-capability as preparational part of project planning prior to the actual implementation;
- suggestions for the enhancement of the PDMS-capability;
- a target oriented controlling throughout the whole PDMS-project.

To provide flexible response on company specific requirements, a methodical approach has to be adaptable to additional process modules, which might be derived from the *strategic management* like the so called *Business Process Reengineering* (Feldhusen and Gebhardt, 2005a).

Medium-sized companies are demanding dedicated information concerning their actual ability for an effective application of PDMS. On the one hand the decision for introducing such a cost-intensive system should be backed up; on the other hand the planning reliability should not be affected. The current stage of a company's ability for deploying these systems is defined as PDMS-capability (Feldhusen and Gebhardt, 2005b):

The PDMS-capability describes a company's capability to effectively deploy a PDMS at a certain time with respect to the predefined targets.

The PDMS-capability is a variable evaluation parameter. Depending on the point of evaluation it is possible to measure the changes in company's suitability induced by conducted improvements steps. The „*Current-PDMS-capability”* describes the actual state of preparation for a system implementation. After introducing PDMS to a company, the measured grade of fitness is defined as *„Nominal-PDMS-capability“*. At this point both types of capability are ideally identical.

The determined PDMS-capability helps to estimate the overall efforts for introducing a Product Data Management System. A reliable indicator for the supposed effort itself is the so called *PDMS-maturity*. This indicator classifies the PDMS-capability in four different grades, starting from non-restrictive (value 1) to not PDMS-capable (value 4), allowing first conclusions for expenses and the aptitude of the enterprise intending the implementation.

Furthermore the PDMS-maturity consists of separate „perspective-maturities“, describing the PDMS-capability of decided company-perspectives like the actual practicability of specific processes or products. Those perspectives are derived from parameters belonging to the PDMS-capability. These *PDMS-influencing parameters* are:

- defined strategic targets, for example the location spanning unification of product development processes;
- the resulting operative targets like an enhanced status of standardization of products or processes;
- the PDMS requirements concerning the IT-infrastructure as well as the standard functionalities provided without any additional customizing efforts;
- requirements comprising products, processes, organizational structures and the representing models in relation to the actual eligibility of system implementation; exemplary parameters are the explicit referencing of product data or the complete description of process cycles.

For an economic efficiency evaluation of PDMS-projects, the PDMS-capability and the PDMS-influencing parameters are essential input values. A more in-depth consideration of economic aspects is described in (Schöttner, 1999; Eigner and Stelzer, 2001; VDI2219, 2002; Stark, 2006).

3 Introducing the Evaluation Approach

3.1 Holistic Approach and PDMS-control Circuit

In the previous chapters the requirements for an effective method, providing the possibility to evaluate a company's PDMS-capability were introduced. The following approach is designed as a control circuit, shown in Fig. 1, and fully meets the mentioned requirements. The continuative description and concretion is adduced below.

Initially the desired *nominal company condition* (TO-BE) has to be identified. Thereafter the *current state* (AS-IS) is determined and evaluated referring to the PDMS-influencing parameters. A methodical procedure which provides clear instructions is obligatory and should in addition feature the opportunity of marking existing room for improvements based on the evaluation results. In this context the value of the identified difference represents the actual PDMS-maturity and is classified as *actuating variable e* within the control circuit.

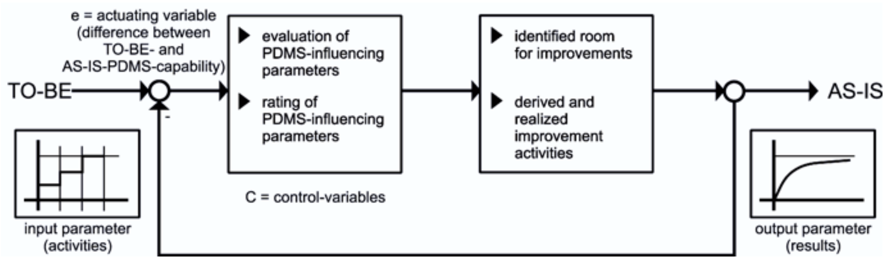

Fig. 1: Control circuit for estimating and enhancing the PDMS-capability

If a difference between both states occurs, an iteration cycle with targeted interventions has to be conducted to minimize the measured deflection. Afterwards the aberration can be quantified and reviewed again by utilizing the PDMS-influencing parameters. They represent the *control variables R* as displayed above. The iterative alteration of control input as well as the subsequent control mode are schematically shown in Fig. 1.

Based on the described control circuit the methodical approach for evaluating the PDMS-capability is developed. It consists of the modules *definition of objectives*, *activities for achievement of objectives* and *evaluated degree of objectives*. Each module itself consists of several single steps. Fig. 2 visualizes the modules and steps of the introduced methodical approach.

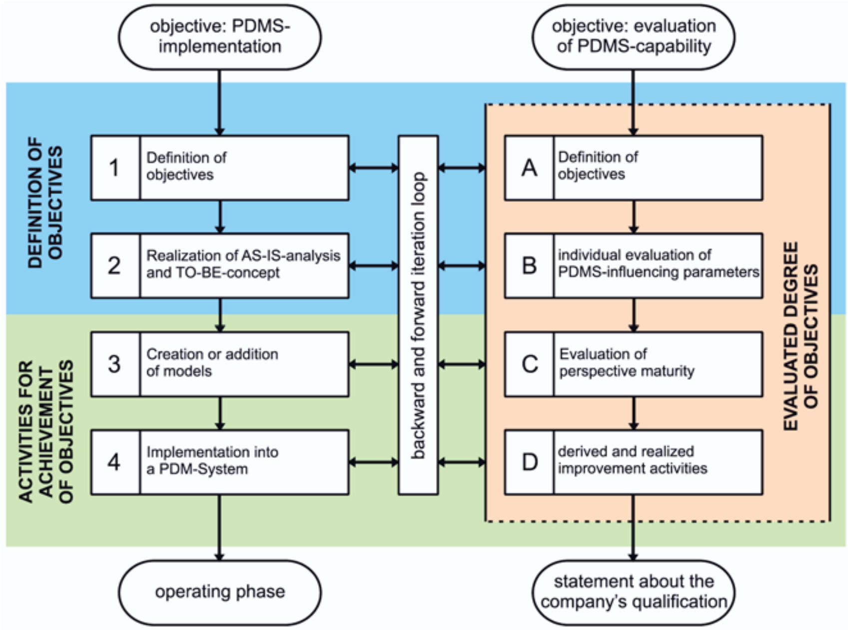

Fig. 2: Steps of the three modules „definition of objectives“, “activities for achievement of objectives” and “evaluated degree of objectives”

The tool for evaluating the actual PDMS-capability is the *Capability Scorecard* (CSC). For a reliable measurement, a company specific methodical evaluation of the PDMS-influencing parameters used by the CSC is essential. Resulting directives are embedded in the superior and recursive *methodical PDMS-introduction*. This ensures an immediate iteration to enhance the PDMS-capability. The company indirectly holds a standardized procedure as roadmap for a PDMS-implementation. A detailed description of the methodical PDMS-introduction is published in (Feldhusen et al. 2006b).

The results of each step are achieved deploying adequate methods e.g. the AS-IS-analysis. Even the single steps are as far as possible in a chronological order, iterations between them are reasonable and inevitable. The realization of essential improvement procedures simultaneously takes place within the affected process. Thus the content is target-oriented, supplemented and supported by prior evaluation and allows constant controlling throughout the whole PDMS-project. Critical influences are allocated in early stages and can consequently be eliminated.

3.2 Definition and Structure of the CSC

A company's current capability for deploying a PDMS is described by the PDMS-influencing parameters. Being of more general character they have to be specified and evaluated for each enterprise. The *Capability Scorecard* (CSC) is the tool which can assist here.

The Capability Scorecard is defined as a methodical approach for evaluating the current PDMS-capability of a company, which considers strategic PLM related targets as well as it takes their interactions and PDMS-parameters to account (Feldhusen and Gebhardt, 2005b).

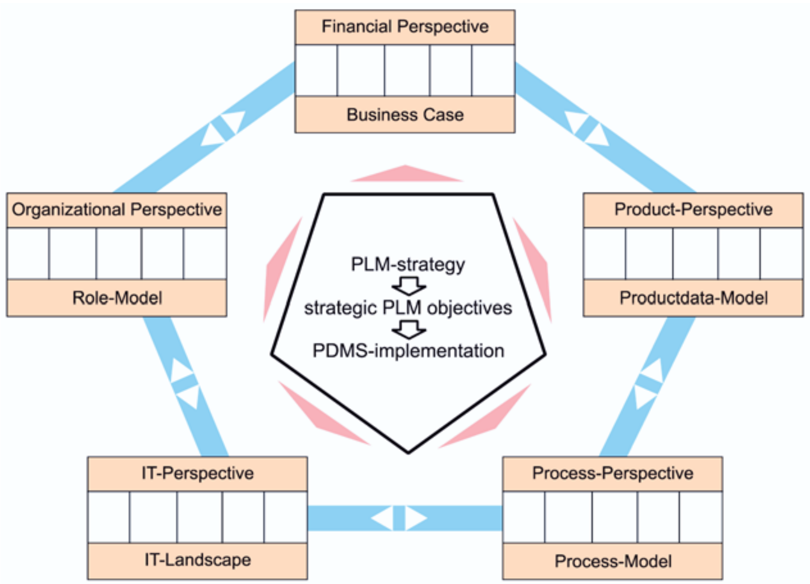

Fig. 3: Structure of the Capability Scorecard (CSC) with the five perspectives, each described by an Activity Matrix (AM)

The aim of utilizing the CSC is to determine the PDMS-capability, which is expressed by the PDMS-maturity. Its purpose is to implement PLM strategies with concrete advice. At the same time it offers the ability of monitoring the changes in PDMS-capability effected by accomplished improving activities. Fig. 3 illustrates the CSC-structure.

Basis for the development of the CSC is the so called *Balanced Scorecard* (BSC; Kaplan and Norton, 1996). In comparison to most other evaluation methods, the BSC incorporates strategic approaches including derived targets. Additional reasons for this choice are a clear structure, an ease of use and a deep understanding for the management and the employees (Feldhusen and Gebhardt, 2005b).

The strategic targets, presenting a major part of the CSC, should be achieved with the help of PLM-strategies and the support of PDMS. Beside financial aspects the PDMS-parameters are also taken into account as objectives are devised. In the style of the BSC they are defined as perspectives and represent the company's essential views for a successful system implementation.

Following perspectives are integrated into the CSC:

- The *Financial Perspective* enables an assessment concerning the economic potential of introducing a PDMS. Companies often describe this perspective as the most essential one. Typically the assessment examines the profitability regarding common financial indexes like the *Cash-Flow*. (Eigner and Stelzer, 2001; Schmidt, 2002; VDI2219, 2002).
- The *Product-Perspective* considers the actual adequacy of products to achieve the defined targets by help of a PDMS. Relevant evaluation criteria are e.g. the complexity of product structures or the state of standardization.
- As part of the *Process-Perspective* the processes to be evaluated are measured concerning their current practicability of being implemented. In this respect the number of sub-processes and the completeness of documented process data are the main indications.
- The *IT-Perspective* analyses the existing IT-infrastructure. This concerns system-requirements as the compatibility of system interfaces or an adequate dimensioning of network topologies.
- The *Organizational or role-specific Perspective* examines a company's structural organization with respect to PDMS peculiarities. Special interest lies on the explicit and entire assignment of rights regarding data objects.

Each perspective is represented by an A*ctivity Matrix (AM)*. Fig. 4 displays the matrix belonging to the Process-Perspective. Within the AM the transfer from strategic into operative level is conducted. Also the actual evaluation of the PDMS-capability is performed by using models representing each perspective. The *Financial Perspective* is featured by „Business Cases" (Schmidt, 2002). The other perspectives are described by a product data model, specific process models and a role model.

As shown in (Eigner and Stelzer, 2001; Spur and Krause, 1997; Feldhusen et al. 2006a, 2006b), the mentioned models comprise all PDMS-influencing parameters and are controlled by PDMS-functionalities. Therefore, an evaluation of the PDMS-capability has to take the compliancy of concrete system-functionalities into account. The more functionality can be deployed without any changes in models, the higher is the grade of a model's PDMS-capability. In addition, perspective specific criteria are deduced, allowing instant evaluation with cost-benefit analysis. Generated results signify the required reengineering efforts for implementation. Utilizing a *weak-spot* *analysis*, target oriented improvement strategies can be induced. The described context specifies the essential structure of the AM.

activity matrix PROCESS				
considered process	**operative objectives**	**evaluation criterias**	**evaluation results**	**derived activities**
process-model "creation of prototypes"	• reduction of running-time to 4 days max. • increase of process-transparecy • reduction of error ratio about 10% • reduction of process-interfaces • ...	1. level of process-complexity 2. level of process-flexibility 3. level of process-interaction(s) 4. ...	perspective-maturity "creation of prototypes": 2,87	• definite process-activities • definite data-collection for process-activity #1020 • creation of a structured database-storage for prototype-data (CAD-models, documents etc.) • ...
process-model				

Fig. 4: Structure of the *Activity Matrix „Process"* illustrated by the considered process "creation of prototypes"

3.3 Example of an Evaluation in Industry

As part of the methodical approach a *weak-spot analysis* was conducted. The results of the examined process "creation of prototypes" are shown in Fig. 5. In the examined company, customer individual prototypes were created by the responsible engineering designer accessing already available products which nearly met the requirements. All respective documents such as sets of drawings or bills of materials were edited manually without documenting any references. Records were stored by using the analogue form of paper within the archive. This proceeding caused an uncontrolled high number of variants.

A high potential for optimization in the area of the unambiguousness of process data evidently exists. The lower the measured value and the greater the area of a single assessment criteria, the higher is the potential for optimization. Exemplary methods like the creation of structured database-storage for prototype specific data or the application of existent software-tools to digitally create prototype documentation as shown in Fig. 4 were utilized to improve the current state.

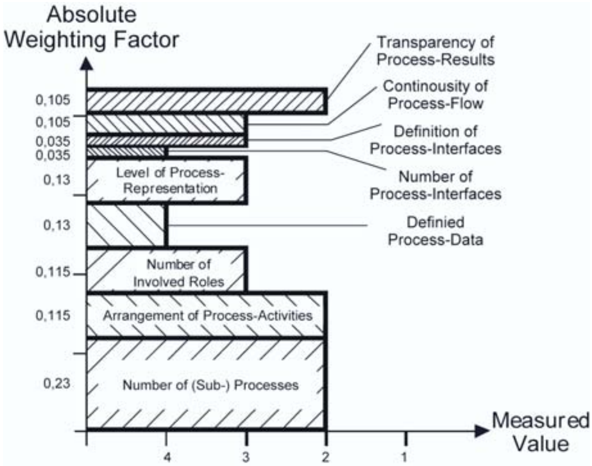

Fig. 5: Weak-spot analysis of the process "creation of prototypes"

After application of the business process reengineering to the investigated process on the basis of the identified optimization potential, process maturity increased drastically: the PDMS-maturity was enhanced from 2.87 to 2.15 underlining the efficiency of this improvement strategy. The goal to increase process efficiency and transparency, especially for department spanning processes was fully achieved.

4 Conclusion and Prospects

This paper introduced an approach which allows evaluating a company's PDMS-capability. The approach consists of two separate modules. The first module realizes the necessary data to ensure a company specific methodical evaluation with respect to the PDMS-influencing parameters.

The second module describes the actual evaluation of the PDMS-capability utilizing the Capability Scorecard (CSC). The CSC consists of five different Activity Matrices (AM), representing each of the influencing parameters. As result a decided measurement for every single variable is conducted. Additionally it provides target-oriented improvement methods, which can recursively be taken into account within the first module. Afterwards an iteration loop is proceeded to evaluate the effects of the previously conducted enhancement. Thus a continuous and purposeful controlling along a PDMS-implementation is assured. To measure and improve a company's PDMS-capability the approach generates reliable output for implementation phases.

Medium-sized businesses will only deploy the CSC if the evaluation efforts are manageable and adapted to their needs. A computer-aided procedure should be preferred and builds the basis for future research projects.

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Lifecycle Information Model for Higher Order Bifurcated Sheet Metal Products

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Abstract

New innovative products and production technologies are increasingly important to strengthen the competitiveness of industry on the global market. To meet basic objectives such as high quality products at reasonable costs and delivery on demand and on time, innovation is a continuously required challenge. Many technical systems are based on concepts resulting from analyzing and understanding nature. Bifurcated structures are basic principles in the evolution of nature in particular to maximize stiffness while enabling light weight structures. Higher order bifurcation products are therefore a consequent approach based on mapping of evolutionary natural principles onto technical systems. The relevance of higher order bifurcation even increases if product and manufacturing innovation are taken into account simultaneously. Within the collaborative research centre 666 "integral sheet metal design with higher order bifurcations" a new product development and manufacturing approach is being developed. This contribution presents the concept of a new lifecycle information model for higher order bifurcated sheet metal products developed in the collaborative research centre 666. The main approach is based on a methodological understanding and a holistic description of the lifecycle. Originating from the lifecycle approach the architecture for a lifecycle phases integrating information model has been derived.

Keywords

Information model, sheet metal, cold forming, high speed cutting

1 Introduction

Bifurcated structures are very important for technical objects. The applications of bifurcated structures are dedicated to e.g. light weight design, enlargement of surface areas, impacting dymanic object behaviour, influencing material flows as well as affecting optic and acoustic product behaviour. Bifurcated structures are applied in many technical applications such as light weight space frameworks, sandwich constructions, longitudinal rolling of shapes or surface shapes for heat exchange.

Traditionally manufacturing of bifurcated structures in particular sheet metal parts requires to premanufacture single parts which are later assembled. This differential manufacturing method, however, often includes some disadvantages. Such disadvantages comprise a couple of weaknesses such as unrequested thermical impact in case of welded connections or nonconstructive stress concentration in case of screwed or riveted joints. Furthermore differential components are typically heavier, error prone and more expensive.

New scientific methods are needed to allow and to support development, design and manufacturing of bifurcated sheet metal products. Manufacturing technologies for the creation of integral sheet metal parts are based on extensive massive forming or cutting processes and constrict the sheet metal product variety.

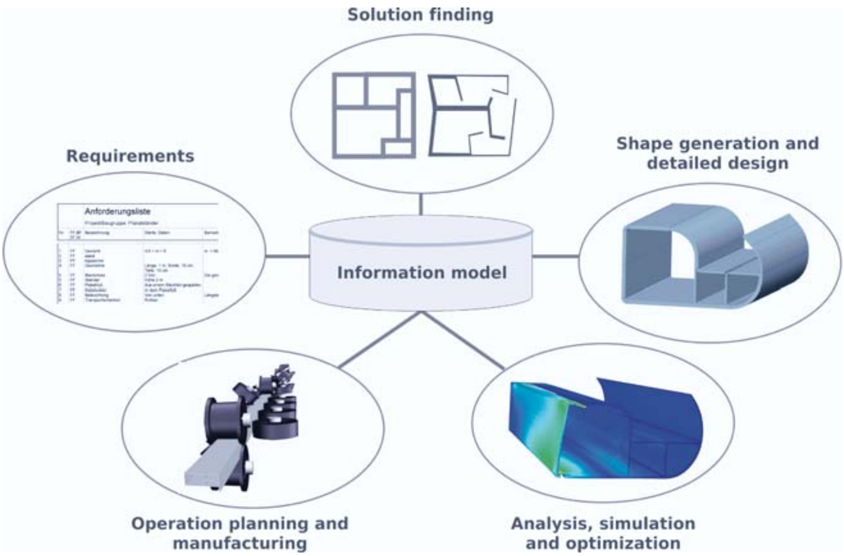

Fig. 1: Holistic approach for integral sheet metal design with higher order bifurcations

Based on this analysis the collaborative research centre 666 "integral sheet metal design with higher order bifurcations" [1] has been founded. The research focus of the collaborative research centre is based on a holistic approach covering all phases for the creation of bifurcated sheet metal products starting from the functional specification and ending with the manufactured sheet metal products. This approach takes into account solution finding, shape generation and detailed design, operation planning, analysis, simulation and optimization as well as manufacturing. In Fig. 1 the holistic approach for integral sheet metal design with higher order bifurcations is shown.

The integration of splitting processes and cold forming of sections by bending sheetmetal in combination with HSC-processes is one of the defiances of the CRC 666. Through the availability of these new manufacturing technologies a new potential for the development of sheet metal products has been provided. The challenge, however, is to enable product developers to design and engineer bifurcated sheet metal products in an integrated product creation process which includes product engineering and development processes, manufacturing planning processes, analysis, simulation and optimization processes as well as manufacturing processes. Fig. 2 illustrates the fundamental principle for manufacturing bifurcated sheet metal products.

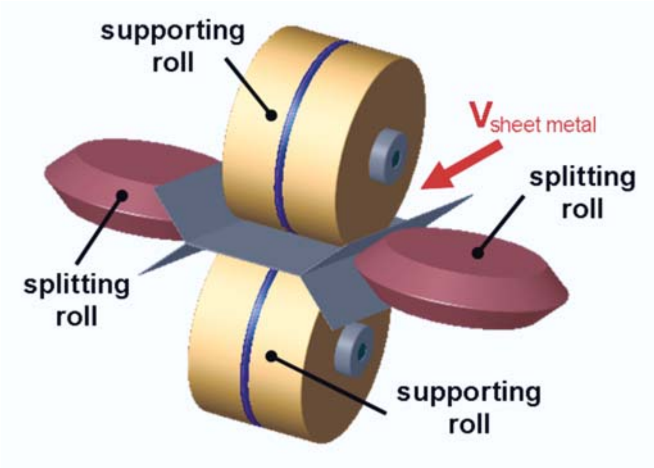

Fig. 2: Fundamental principle for manufacturing bifurcated sheet metal products

A key issue for integral sheet metal design with higher order bifurcations is to provide computer based integrated platforms for a seamless support of the entire product engineering and development processes, manufacturing planning processes, analysis, simulation and optimization processes as well as manufacturing processes. The concept for a seamless computer based support of the whole process chain is to provide an integrated information model representing the engineering solutions of the associated lifecycle phases. The integrated information model and the associated lifecycle phases are bilaterally constraint.

Consequently a lifecycle methodology for higher order bifurcated sheet metal products has to be developed based on which the architecture for the integrated information model is being developed.

2 Lifecycle Methodology for Higher Order Bifurcated Sheet Metal Products

The focus of research of the Department of Computer Integrated Design, TU Darmstadt, is a highly adaptable information model that integrates all product description data for the sheet metal product, all factory data of the manufacturing process and all simulation data of the testing process. The aim of the information model is to consistently link product data, e.g. topologically optimized geometrical representation, factory data, e.g. boundaries of production techniques and process management data. The research activities continue pursuing new aspects of lifecycle-orientated modelling of product and factory data. The lifecycle methodology for branched sheet metal products consists of mapping, integrating and recombining data for collaboration purposes. These collaboration processes occur between different groups of people during the whole process chain of creating branched sheet metal products beginning. This product development process consists of the following stages, each including singular kinds of information:

- Gathering and analysis of the customer requirements for their unique branched sheet metal product. Each anticipated value of any possible requirement has to be reclassified to a concept scheme of outer properties, the so called taxonomy for sheet metal products. This is necessary to set up an algorithm based process to transform the fuzzy requirements into quantifiable values for the inner properties of the desired sheet metal product. The concept scheme will be based on a mesh-like structure, linking related terms. All variables defined at this early point of time are defining and affecting all succeeding product development stages. And vice-versa, all succeeding product stages constrain the range of values for the exact inner properties because of certain restrictions for machine parameters etc. From the information technology point of view, it has to be assured to map the information of customer requirements, outer and inner properties in a highly adaptable manner to guarantee the capability of development for both the product creation process as well as the involved technologies.

- All exact inner properties for the desired sheet metal product regarding the appearance are passed on to two-pass mathematical optimization procedure. The first instance of this optimization process determines the mathematically optimal geometric shape and topology of the sheet metal product. The term topology in the sense of this paper describes the way and order of operations the sheet metal part is bent and spitted. It must not be misconceived as actual location of e.g. vertices and edges in the sense of the geometrical representation.
- This optimization is done by mathematical algorithms considering expected loads and gain improved strength properties for the component. The second instance especially defines a valid unrolling for the sheet metal component taking into account the various production restrictions. Usually there is a vast amount of possible unrolling, i.e. the sequence of flow splitting and bending processes, for a single product. This means there also has to be any kind of information management for different versions of one product in the lifecycle information model. All information regarding the unrolling is mapped into the solution finding part of the information model.
- In the next step the 3-D model of the 2-D representation of the unrolling is created. This is done automatically by an extension for the CAD-System of the designer. This extension is connected to the main information model and uses the information of the 2-D representation. The main information model contains a geometry data model that comprehensively and non-ambiguously describes the geometry of the optimized integral sheet metal parts with higher order bifurcations. The only thing the engineer has to do manually is to add features like holes, chamfers etc., which represent the result of the integrated HSC-processes in the bending and splitting processes. The result the 3D designing instance is a fully detailed 3D-model of the sheet metal component. Again, new information is gathered. The representation data of the 3D-model is mapped into the product model part of the main information model.
- As now the design phases of the product lifecycle are passed, the next steps are the production planning for the desired sheet metal product, the production itself, the evaluation of the produced product and the backflow of newly attained process knowledge. To produce branched sheet parts in a continuous production line with a high output, the entire production line has to be planned in detail. Important information for this planning is the determined geometry of the part, the chosen unrolling of the product, technology constraints, known machining limitations and

constraints as well cost and cycle time data. This given information can be used to set up a virtual simulation for the entire production process to ensure the operational reliability of the facility. Virtual test runs support this process. Again all simulation results as well as the production line configuration and the used virtual parameters are linked together to one configuration set. This configuration set is mapped into the information model and referenced to all relevant base information. This part of the information model is a factory data management instance of the main information model.

- This factory data model also consists of the machine parameters of the real production process of the branched sheet metal product. Every production run represents accumulated sets of machine parameters for all involved processing steps. The arrangement of the single processing steps in the production line is registered as well.
- To evaluate the material characteristics and the durability of the produced sheet metal part, destructive and non-destructive material test are performed. The outcomes of these tests are analyzed for new technical expertises.

While the various new technologies are consecutively enhanced, several cycles during the branched sheet metal product creation process are conducted to optimize the results of the creation process and to achieve planned properties for the final product. In particular, the geometrical product modelling process will be highly dependent on results of the production planning and the production simulation process. Each previously not assessable shift of any production constraints, e.g. maximum split depth or previously unrealized restrictions, will force to readapt the geometric model of the product. The early phases of mathematical optimization are hinge on the possible machine parameters in quite same way. And of course the evaluation of the final products will led to necessary adjustments in the optimization algorithms, geometric modelling as well as setup for the production line.

Especially all technological improvements trigger a technology-push towards the early phases of developing sheet metal products. A common lifecycle-oriented approach aggregating all product information regarding any stage in the lifecycle improves the quality of information exchange between downstream and upstream lifecycle stages.

In particular the tight informational interdependencies between products properties, optimization, design, process planning and manufacturing need to be supported by a flexible and consistent information base covering the entire lifecycle of sheet metal products of higher order bifurcations.

3 Information Model Architecture

A seemless integration of product information throughout all phases of the product lifecycle can be provided through an integrated information model [2, 3, 4]. In CRC666 an integrated information model for sheet metal products of higher order bifurcations is developed which represents on one hand the respective lifecycle phases and on the other hand the dependecies between the lifecycle phases in different details.

Fig. 3 shows a high level view of the architecture of the integrated information model which consists in three major components:

- the representation of the respective lifecycle phases (design, analysis, process planning, manufacturing and resourcing),
- the integration of the phases (integration core) and
- the management of lifecycle and lifecycle integration [5] (management).

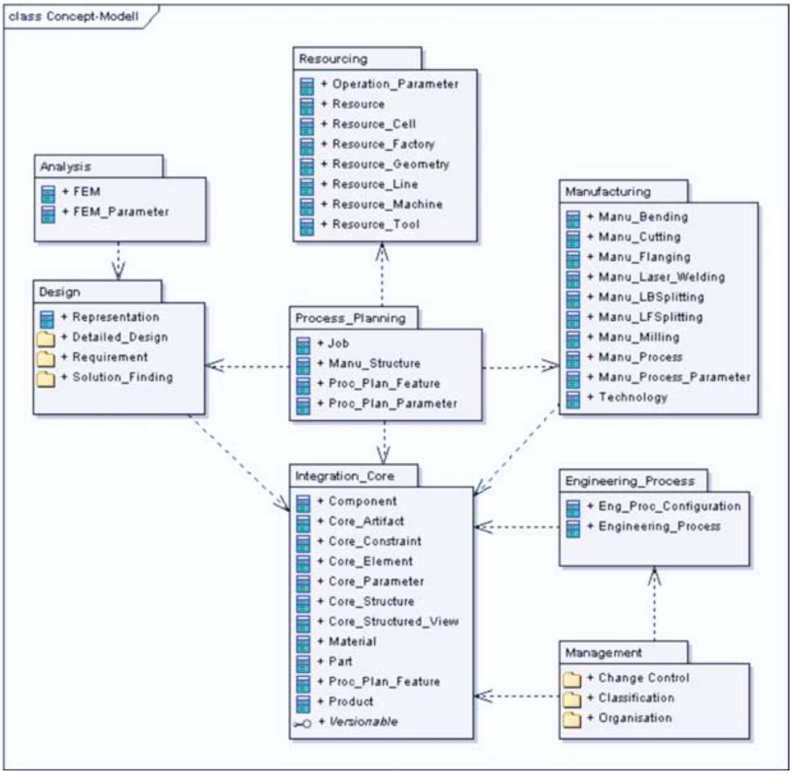

Fig. 3: Architecture of the integrated information model

In the *integration core* the abstract *structure*, *element*, *parameter* and *constraint* are represented, which generalises the common aspects throughout all the lifecycle phases. Based on the *integration core*, the lifecycle phase specific representations: *designt, analysis*, *process planning*, *manufacturing* and *resourcing* are built by specifying the appropriate classes in the core.

The lifecyle phases from requirement specification to detailed design are represented in the lifecycle model *design,* which consists in turn in the lifecycle models *requirement*, *solution finding* and *detailed design*. The analysis information during the development is represented in the lifecycle model *analysis*. Information about processes and resources are represented in the lifecycle models: *manufacturing* (a taxonomy about processes) and *resource*. Based on the component *design*, *manufacturing* and *resourcing* information, *process plans* can be modeled and optimized with the lifecycle model *process planning*. Integrated process chains can be modeled with the lifecycle model *engineering process*. In the lifecycle model *management* change control, classification and organisational information are represented.

In the following paragraphs, the *integration core* and the representation of the lifecycle phase *development* are explained in detail.

3.1 Integration of the Lifecycle Phases

In order to integrate the entire lifecycle from development to manufacturing, integration on different level of details in the represention of lifecycle phases is required: on the model structure level, on the model element level and on the parameter level. Fig. 4 shows the most important classes in the integration core.

On the high level, the structural integration is supported through the class core structure view, which consists in core structure, core element and core parameter. Respective lifecycle structure views like the structures in requirement specification and development (solution tree, geometric structure and analysis structure) can be built by specifying the core structure view.

On the element level, the lifecycle phase specific element can be integrated through the common abstract core element.

On the parameter level, cross-lifecycle-phase constraints between the parameters for parametric cross-model integration [6] can be established.

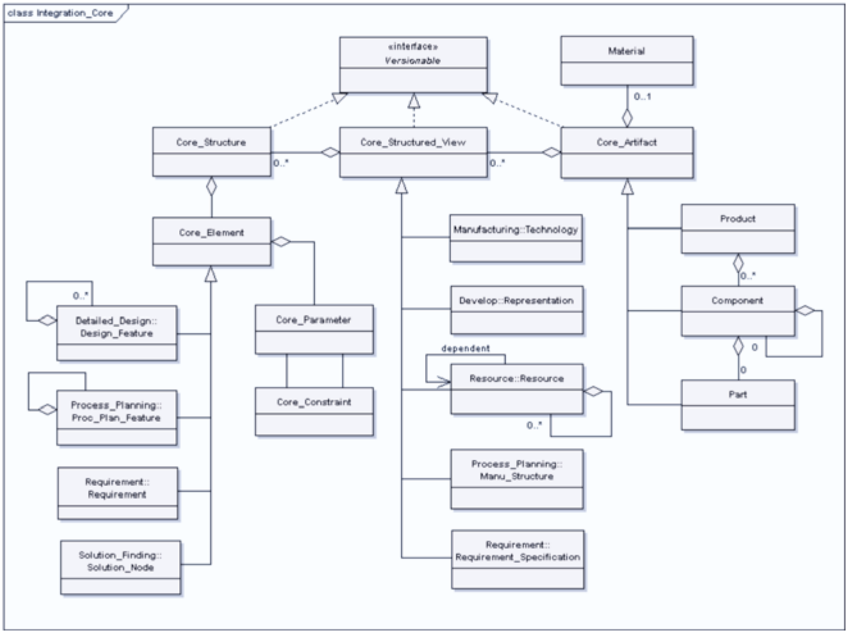

Fig. 4 The integration core of the information model

3.2 Representation of the Lifecycle Phases

To efficiently support activity in the particular lifecycle phases, the lifecycle phase specific structures and element informations have to be properly represented in the respective lifecycle models.

Fig. 5 shows the most important classes to represent the information in the early lifecycle phases. The development of higher order bifurcated sheet metal products is based on an algorithm-based approach. The solution finding is based on mathematical optimization of the form and topology of the bifurcated sheet metal product. The result of the mathematical optimization is a tree representation of the product: the *solution tree*. A solution tree is made up of *solution nodes* and *solution edges*. Solution nodes represent the manufacturing features like bending, flanging, and linear flow splitting etc. The sequence of the nodes is represented by the solution edges. Solution nodes have 2D- geometric informations. So on the grounds of a solution, the 2D-geometry and unrolling can be defined respectively, and by sweeping the profile, a 3D-shape can be created.

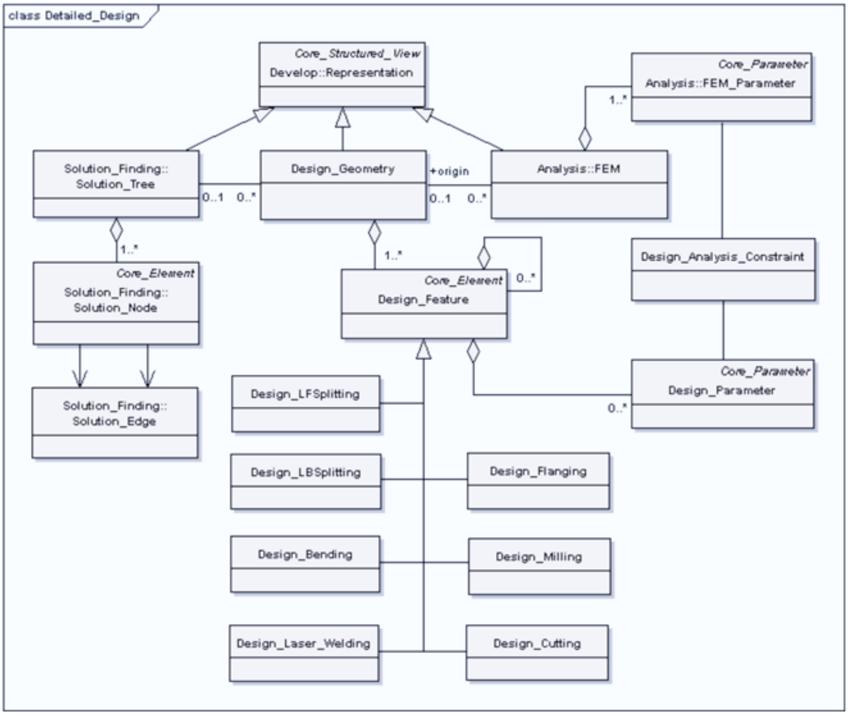

Fig. 5: Representation of product information in ther early lifecycle phases

In detailed design, the 3D-geometry design of the profile will be at first generated with the help of design features on the basis of the solution tree and the design engineer can then modify the design functional and aesthetic by detailing some geometric aspects with detailing features like drilling, milling etc. Design features represent the geometric representation.

The integration between solution finding and detailed design can thus be achieved by the transformation of the solution tree to the geometry structure made up of design features. Constraints can be built between the parameters of the solution nodes and of the design features, so that a geometric change on the profile in the solution can be automatically hands on the design geometry.

In analysis, FEM-model is built on the geometry of the detailed design. Sometimes defeaturing will be undertaken. Constraints between the geometric and analysis parameters can be eventually built to integrate the design and analysis. The structural transformation from design to analysis and the parametric integration of design and analysis is still in the development.

4 Scenario Product Development

On a scenario for the development of a poster stand, the concept of the integrated information model is illustrated. The detailed design starts with a solution tree. To generate the 3D-geometry, the solution tree will be transformed in to the gemetric representation. The solution tree is represented in an XML-file. The scheme for the XML-file is defined by the lifecycle model for the solution tree in the integrated information model. In the lifecycle model for solution finding, specific solution nodes like *flange*, *bend* and *lfsplit*.are defined.

In Fig. 6 to the right, an instance of the solution tree in XML results from a mathematical optimization process is presented. The solution nodes *flange bend* and *lfsplit* has also 2D-geometric informations such as *flange length*, *bending* or *gap angle*, *radius* and *material thickness*. The concrete sequence of production by a lining up of *bending* and/or sheet metal splitting processes is also defined in this XML-file.

To generate the concrete three-dimensional geometry these solution nodes are tranformed first into the design features, and then over the API of the respective CAD-system in UDFs (user defined feature), which forms the final geometry of poster stand. In Fig. 6 to the left, the poster stand is automatically generated in a CAD-system from the solution tree at the right side.

So the integration of solution and shape generation can be achieved through the structure tranformation of the lifecycle model of solution finding and detailed design.

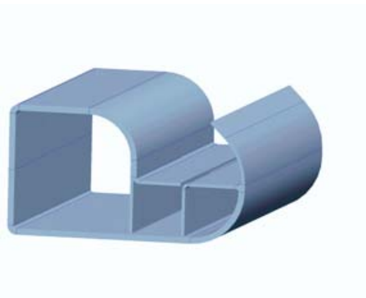


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Fig. 6: Scenario in product development

5 Summary

The research focus of the collaborative research centre is based on a holistic approach covering all phases for the creation of bifurcated sheet metal products. A key issue is to provide computer based integrated platforms for a seamless support of the entire product lifecycle. A concept based on a lifecycle methodology and an architecture for the integrated information model is presented in this paper.

The architecure consists in three major components: lifecycle model for the respective lifecycle phases, integration core for the integration of the lifecycle phases and the management of information and process.

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Simulation-based Multiple Project Management in Engineering Design

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Abstract
In this paper a person-centered, actor-driven project simulation approach is presented that can cope with highly parallel tasks in multiple projects and can, therefore, help managers to plan concurrent product development projects. The task execution sequence is determined by means of a bounded rational choice model accounting for the urgency of tasks. The model creates realistic project dynamics using only a small number of input parameters. The project manager is, for instance, not forced to specify fixed predecessor-successor-relations of tasks. The model was validated with historical project data from a company of the German electronics industry. Using Student's t-tests the simulated project durations showed no significant derivation from the historical duration.

Keywords
Multiple project management, simulation, bounded rational choice, product development

1 Introduction

Product development projects nowadays are carried out according to the Concurrent Engineering paradigm. As a result, the number of persons involved in product development projects and the number of concurrently performed projects permanently increases [21]. The process of managing such parallel projects is often referred to as *multiple project management*. When the underlying tasks use the same personnel and resources (tools, labs, test centers) the management of such multiple projects is quite challenging. Research on Project Management proposed many methods, for example, the well-known Gannt-Charts, the Critical Path Method or Program Evaluation and Review Technique. With respect to the challenges of Multiple Project Management though, these methods and tools provide effective support only in theory. For instance, it is not possible to model and simulate iteration loops and resource dependencies adequately. Furthermore, probability distributions of task durations are considered to be independent, which is obviously untrue for closely interacting development tasks. Also, dependencies of the resources - like computer-aided design tools – and the available personnel are not considered. Last but not least, the bounded rational working behavior of product developers cannot be reflected. However, this behavior can be considered as a major reason for schedule risk in product development projects [20].

In conclusion, the classical methods of project planning have significant shortcomings when modeling and simulating dynamic and concurrent product development projects.

2 Related Work

These shortcomings strongly stimulated research in simulation of complex product development projects since the 1990s. Simulation models of product development processes can be distinguished into three differently abstract approaches: system dynamics models, discrete event process models, and discrete event queueing models.

System dynamics models of product development processes [9, 11, 23, 29] are continuous models where some abstract variables of interest (stocks) can be increased or decreased by flows and, thus, be influenced by feedback and feed forward loops. Since single tasks and resources cannot have properties and, hence, cannot be distinguished, system dynamics models may have shortcomings when supporting operational project management. The problem of resource induced task interdependencies cannot be mapped with a (known) system dynamics approach.

In *process models* of product development projects the model structure usually maps activities and precedence relations between activities. The dynamic elements that virtually "flow" through the structure are events (e.g. activity finished) and/or resources (persons, tools). The majority of the process models described in literature [3, 4, 8, 10, 12, 26] assume that resources cannot be limited. These models are, therefore, not capable to map the problem of resource-induced task interdependencies. Some process models account for limited resources [5, 14, 15, 16, 22]. However, they (1) assume the task durations to be independent of each other and (2) assume the modeled product developers as trivial resources. Hence, there is no process model that is capable to model the bounded rational behavior of product developers with respect to the urgency of tasks or personally preferred working styles.

In *queueing models* of product development processes the progress of a project is generated by actors (persons or organizations) that process some (queued) tasks (work to be done). The tasks can be thought of as the dynamic elements that virtually “flow” through the structure of actors. The model presented in this paper belongs to the actor-driven models.

Cohen [7] and Levitt et al. [17] developed an actor-driven simulation model, the so-called Virtual Design Team (VDT). The simulated persons play an active role in this approach, checking if a valid job is available (as well as the necessary non-human resources) and then processing this job. When more than one job is available in the VDT persons stochastically apply different priority rules such as FIFO, LIFO, or randomness. Other authors elaborated on the VDT-model [6, 30]. Although the problem of resource-induced task interdependencies can be modeled with the described VDT-models, the priority setting rules only partially reflect the bounded rational behavior of human actors.

Steidel [27] developed another actor-driven simulation of product development projects. As in the VDT, the simulated persons process queued jobs. The activities cannot be split and must, therefore, be completed in one step. Thus, the problem of resource-induced task interdependencies cannot be mapped with Steidel’s approach.

Adler et al. [1] developed an actor-oriented simulation model in which they address the issue of multiple project management. Unfortunately, also this approach only partially reflects the bounded rational behavior of human actors.

Finally, it appears that most of the discussed discrete simulation approaches have been validated quite poorly. Some authors have modeled and simulated real product development projects, however, none have compared the simulation results with historical (empirically observed) data by means of statistical methods, e.g. hypothesis testing.

3 An Integrative Simulation Approach

These reasons were sufficient to develop a new and improved simulation model for the management of complex development processes. The integrative simulation model consists of five partial models: (1) the partial model of the product to be developed, (2) the partial model of the operational structure, (3) the partial model of the organizational structure, (4) the partial model of the working persons involved in the development project and (5) the partial model of tools being used for product development.

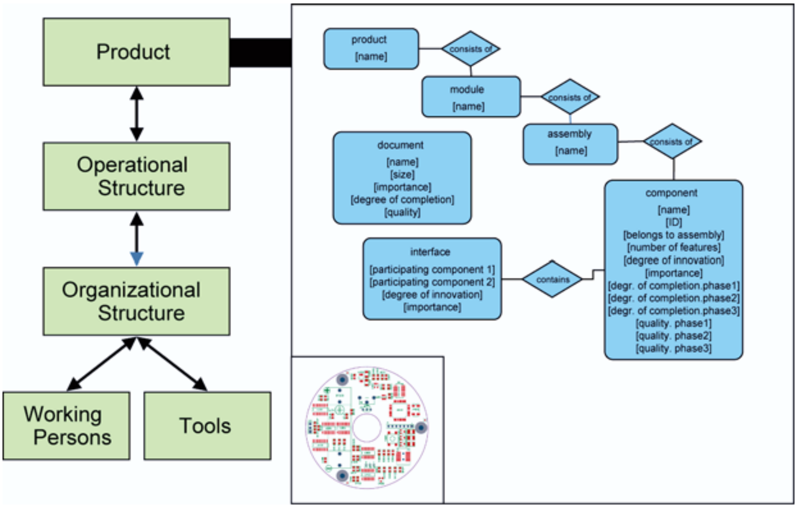

Fig. 1: Partial model of products

The partial model of the *product* to be developed is depicted in Figure 1 as an entity relationship model of different decomposition levels of a product and its relevant properties [25]. The lowest level consists of so-called components that are interconnected by so-called interfaces. Interfaces between parts or subparts often need a close cooperation of the persons involved. Therefore, interfaces in our model can induce communication efforts.

The partial model of the *operational structure* defines tasks and orders of tasks (Figure 2). In computational terms, tasks can be considered as pointers to the work to be done, i.e. components to be transformed. Persons that are responsible for this transformation, adequate tools and resources etc., can be specified here. The most sensitive input variables are the expected workload (man hours) and the deadline of a task. By using the concept of deadlines it is no longer necessary to specify explicit predecessor-successor-relations.

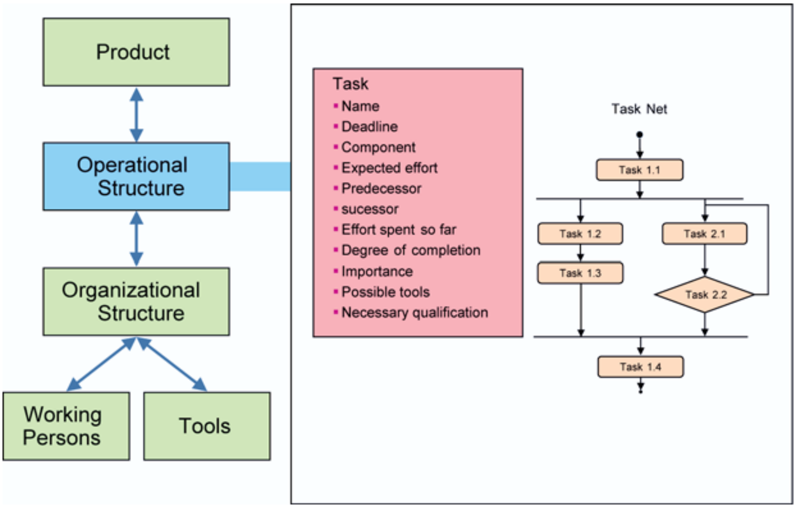

Fig. 2: Operational structure – properties of tasks and a task net with three design phases

Nevertheless, it is also possible to define explicit predecessor-successor-relations. In doing so, milestones between design phases can be defined. In case of not fulfilling a defined target quality, a project leader can reassign particular tasks to the respective person to increase quality. In order to proceed with a task of a subsequent phase all tasks of the previous phase have to be completed. Thus, the concept of so-called quality gates is realized in the simulation model. The mentioned definitions can be carried out in a so-called task net.

In the partial model of the *organizational structure* organizational relations and dependencies are defined. Furthermore, the organizational structure defines who is authorized and competent to use the right tools in the development process. An organizational unit can be either a position that is an organization of the lowest possible order, or an organization of higher order (Figure 3).

The most important partial model is the *model of the person* (Figure 4). The simulated persons are the driving force to initiate any action in the development project. We therefore call our approach “person-driven“ or “actor-driven”. In other words, the simulated person decides which task to process next and how to process it. The model works like a queuing system, meaning a person has an “in-tray” with tasks to be processed.

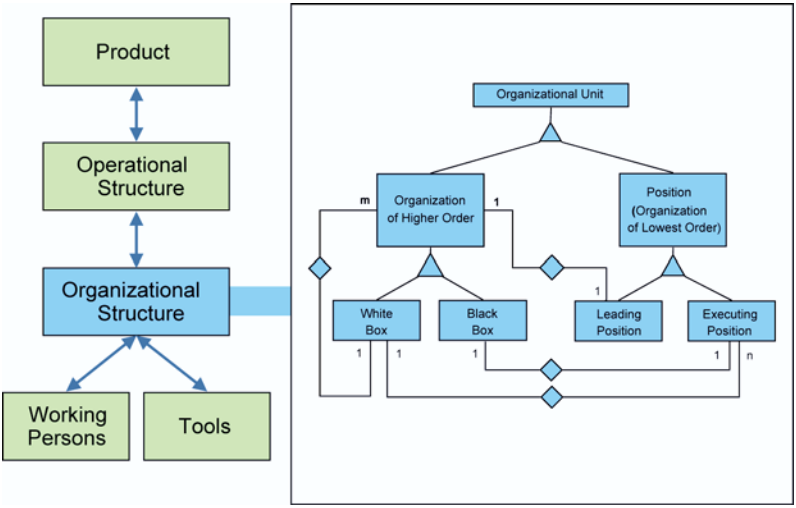

Fig. 3: Organizational structure of a team

According to a bounded rational decision model as described in [18, 20, 24] the person chooses the task to be processed next.

Then, the person processes this task for a certain time. However, after some time the person reconsiders if, in between, another task has a higher priority. In that case the other task is processed next. When a task is finished it will be sent to a pool of "done tasks".

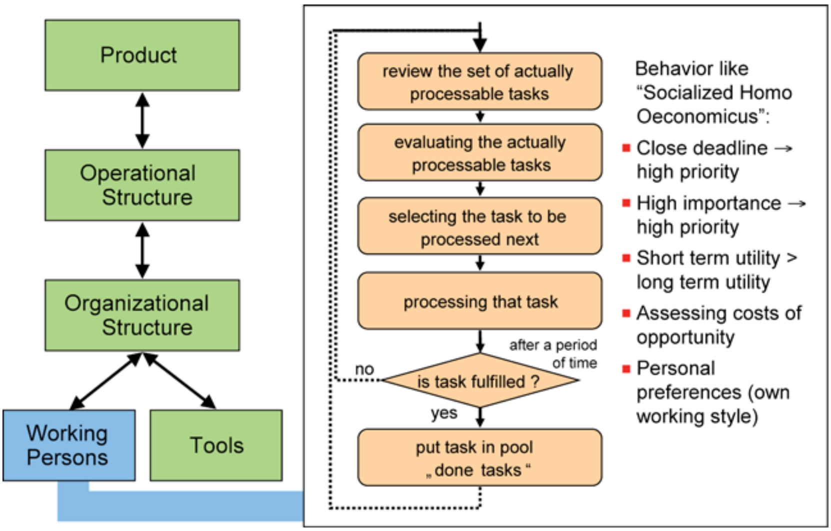

Fig. 4: Task processing of the simulated persons

When persons choose between concurrent tasks, we relied on bounded rational decision making theories [2, 13, 28]. If compared with economic approaches, our actors may be considered as "relatives" of the so-called "socialized homo oeconomicus". This implies that decisions are based on goals and utility but also account for irrational measures like a temporal distance of rewards. For instance, a task with a close deadline will be assigned a high priority and a task with high importance for the company will also be assigned a high priority. Furthermore, if a person permanently processes a task, the priority of the task decreases over time. A person additionally assesses opportunity costs. Therefore, the person evaluates how much time to spend for getting familiar with a task. The simulated persons try to avoid opportunity costs and wait until the task is truly urgent.

There are several additional concepts being covered by our person models like communication skills, work experience, etc. For further details the reader may be referred to [20, 24].

The simulation model now adequately models resource-induced task dependencies using individual efforts in terms of workload (man hours) for single tasks as input parameters of the simulation.

The model is capable of simulating two or more projects with parallel access to common resources. The model can also account for any other (e.g. regular) work to be done – the additional tasks are simply put into the "in-tray" of the simulated person.

Last but not least, the simulated persons can use several tools for carrying out their development work. Tools are enabling resources for certain development tasks - for instance in detailed engineering - and have an impact on individual performance. With our *tool partial model* we modeled functional dependencies such as the influence on workload when processing a tool-supported task. In order to keep the model simple, we did not model all available software or hardware tools in product development, but only such tools that can be bottlenecks – for instance, expensive CAD software tools.

4 Model Implementation and Verification

The conceptual model was transferred into a formal quantitative model. Therefore, the formalism of Timed Stochastic Colored Petri Nets was used. After implementation with a standard Petri Net simulation software the model was verified. That is, by means of systematical experiments the consistency of the computational with the conceptual model was checked.

In order to be able to verify the simulation model a large number of simulation experiments on the basis of "toy problems" were conducted. Differently complex task nets were implemented and simulation runs with systematic parameter variations were computed.

5 Model Validation

In order to validate the simulation model we collected historical project data in a company of the German electronics industry. The company develops and manufactures electronical and mechatronical components and modules. The considered development project included tasks like conceptual design, designing and calculating connection diagrams, doing layout designs of circuit boards, etc. The collected data provided information about all five partial models. With respect to the efforts spent for each task the data of a barcode based labor time system could be accessed. This labor time system stores the real working hours of the product developers on specific tasks on a very fine-grained level (30 minutes accuracy).

The simulation model was parameterized with this data and simulation runs were conducted. In Figure 5 the historical task progress and a typical simulated task progress are exemplarily depicted for the task "conceptual design.

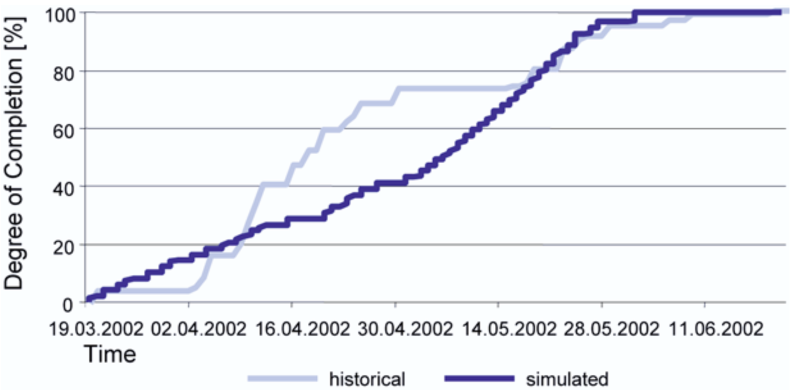

Fig. 5: Historical and typical simulated course of completion of task "conceptual design"

The simulation results were reviewed by some experts of the company. They admitted that most of the tasks were simulated realistically. The large amount of fine-grained empirical data of the development work processes allowed us to formulate the crucial null hypothesis for a project planner. This is "The total cycle time of the real development project and the total cycle time of the project simulation model do not significantly differ”. In order to test this hypothesis by means of inferential statistics, a sufficiently large number (n = 200) of simulation runs were computed and the output was analyzed. The normal distribution of the output data was validated with the Kolmogorow-Smirnow test. Finally, we were able to test the null hypothesis with Student’s t-test. The simulation results showed that the null hypothesis could not be rejected. That is, no significant differences between the real project duration and the simulated durations occurred. Moreover, a sensitivity analysis was carried out in order to study how the output changes if the main input parameters are varied.

6 Conclusion and Implications for Multiple Project Management

In order to plan multiple projects with the presented approach a project manager must first of all only define tasks with estimated efforts and deadlines and assign these tasks to persons. Efforts to be spent can be better estimated by project managers than task durations since durations depend on the course of concurrent tasks. Compared with existing approaches this enables a more intuitive modeling process. Fixed milestones can be defined in the task net. The simulation results consist of virtual courses of action for the projects. While exploring the results the project manager can assess if the assigned deadlines can be met. With trial and error he or she can then change some input measures (deadlines, assignment of work to different persons, experience of particular persons, etc.) and assess the output measures of interest. For a more detailed analysis the project manager can model the underlying product structures in order to map information needs or bottleneck tools that could potentially influence the course of the simulated projects.

7 Acknowledgements

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Towards “The Timeless Way of Product Lifecycle Management”

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Abstract
Pattern languages were originally invented in the 70s as an approach to capture design experience in civil engineering and architectural design. During the last decade the approach has been bruit about in the software community. In engineering design as well as Product Lifecycle Management (PLM), pattern languages have yet not been applied. Because pattern languages have been applied in a wide range of application domains, they are supposed to be expedient to manage knowledge in a multidisciplinary environment like PLM. This paper discusses to what extent pattern languages are expedient for PLM and delineates approaches to develop a cohesive PLM pattern language as an interdisciplinary lingua franca.

Keywords
Pattern Language, Product Lifecycle Management (PLM), Knowledge Management, Collaborative Engineering

1 Introduction

Experiences from several decades of industrial production show that products and product creation processes are getting more and more complex. To overcome this complexity engineers need to have appropriate skills and knowledge at their disposal. Accordingly, tools and methods to provide engineers with knowledge are getting more important to ensure the competitiveness and sustainability of a company.

2 Approaches to Provide PLM-Knowledge

Several approaches to provide knowledge exist, which are expedient to be applied in the area of Product Lifecycle Management (PLM). Engineering guidance systems are applied in technical departments to provide information about development processes [1]. They idealize the addressed processes to provide generally applicable information. The structure of the content is either process oriented or product oriented. If in case of a process oriented system information about products and technology is required, the engineer has to know the appropriate location within the according processes. In case of product oriented systems the engineer likewise has to determine the product according to a certain process in order to get information about this process.

Another approach to supply engineers with knowledge is the usage of tools similar to yellow pages [2]. These cluster the relevant knowledge and assign each cluster to an engineer who is an expert in that field and possesses the according knowledge or skills. The system will provide an engineer who searches for information with the contact data of an expert. This approach supports the exchange of implicit information between staff. It is feasible in case of a special problem occurring, but it is not feasible to establish an ongoing flow of information to satisfy the regular need for information.

Even books are tools to provide engineers with knowledge and have to be mentioned in the context of this paper. In their entirety they provide a huge amount of knowledge with various levels of expertise. Each book is structured in a way that the contained information is easily accessible. But the information subsumed by all books as an entirety cannot sufficiently be retrieved in an efficient way. Therefore, books are merely used in industrial environments.

3 Pattern Languages

3.1 The Pattern Approach

As described above, some current approaches are capable to support the retrieval of knowledge according to a certain context utilizing structures or indices. But these approaches focus on specialized ephemeral knowledge. Common knowledge, which every single engineer needs to have at his disposal to originate state-of-the-art results, can still be primarily found only in books. Pattern languages are an approach to provide common knowledge in an easily accessible way. Beyond this, pattern languages aim at some further properties, which are not objectives of other knowledge management approaches (chapter "Approaches to Provide PLM-Knowledge"). Pattern languages were originally invented by Christopher Alexander [3, 4, 5] in the 70s. They were first applied in civil and architectural design to capture design experience and to communicate the according solutions with customers. During the last decade the approach has been bruit about in the software community. Currently, pattern languages have been applied to many fields within computer science. They have gained a strong influence on those fields, especially software engineering and programming [6, 7, 8, 9] as well as human-computer interaction (HCI) design [10, 11, 12]. Even in pedagogy pattern languages have been applied [13].

In engineering design as well as Product Lifecycle Management (PLM) pattern languages have yet not been applied. The domains described above, in which pattern languages have proven to be expedient, are similar to PLM concerning their design orientation, interdisciplinary collaboration and customer awareness. Thus, pattern languages are supposed to provide a similar benefit, if they are applied within PLM. Appropriate approaches will be discussed in the section "Applying Pattern Languages to PLM". The chapter "Summary and Outlook" summarizes the main contributions of this paper and concludes with an outlook on further research. First, the chapter "Pattern Languages" gives a short introduction to the concept of pattern languages and the philosophy behind it.

3.2 Syntax and Semantics

The central idea behind pattern language is that, due to complexity, humans have evolved archetypal concepts, which solve recurrent problems. These concepts are called patterns. Within a pattern language all patterns have a uniform format and structure. The structure of the original patterns by Alexander is constituted by a set of topics [3], which can only be found with minor amendments in other patterns languages:

- The unique and descriptive *name* of the pattern.
- A *ranking* of its quality (omitted in some other pattern languages).
- A *picture* illustrating an example of the pattern.
- The *context*, in which the pattern can be applied. The context consists of the patterns which are supported by the actual pattern.
- A short *statement* delineating the recurring problem referred by the pattern.
- A detailed description of the *problem* comprising a comment on the conflicting forces, which cause the problem. In case of PLM most of these forces are of technical (e.g. an engine should be powerful and ecological),

economical (e.g. a product has to be cheaply producible and competitive) or organizational nature (e.g. short time-to-market and lean value chain). The solution must describe how the forces can be balanced or resolved.

- An archetypal *solution* of the problem illustrated by a diagram.
- References to *supporting patterns*. These references point to other patterns, which "unfold" the solution of the current pattern, for example the pattern "Road Crossing" is supported by the pattern "Raised Wall".

Patterns do not stand for themselves. Like described above, they comprise references to "supporting patterns". This results in a hierarchical structure leading from a most general top-level pattern over larger-scale patterns to elementary ones (Fig. 1). Each elementary pattern can be reached via one or even more ways from the top level pattern. Thus, the set of all patterns belonging to the same language constitutes a semilattice (a partially ordered set closed under either supremum or infimum) with the "supporting pattern"-references as ordering relation.

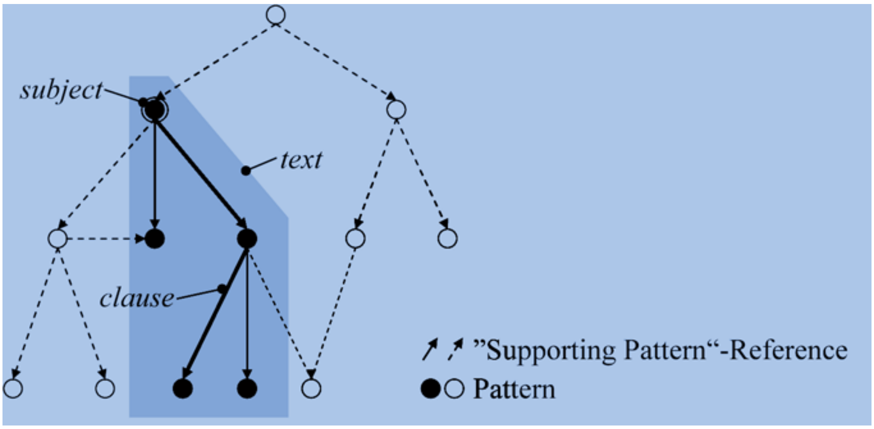

Fig. 1: The structure of a pattern language

This concept can be compared to a spoken language. A spoken language comprises words and grammatical rules, which describe how the words can be related to each other resulting in a clause. If in case of patterns the "supporting pattern"-references can be seen as the grammar of the pattern language. The clauses constituted by this grammar are sequences of patterns describing a set of constitutive solutions. If a problem corresponding to a certain pattern somewhere occurs within the lattice, a subset of supporting patterns is chosen by the user (architect, software developer, designer …), which is subject to his intentions. The other supporting patterns are discarded. Each chosen pattern in turn entails a further subset of chosen supporting patterns. As a result a sub-lattice evolves, with the original problem as the join. The paths down from the join constitute a set of clauses with the original problem as the subject. This set can be seen as a text, which is written in the pattern language, expressing the user's ideas of solving the problem.

4 About Pattern Languages in PLM

PLM is a strategical approach to manage the entire lifecycle of a product and its components to ensure sustainable benefit. It can be seen as a meta-theory integrating theories and methods from discrete subareas within the product lifecycle, like marketing, industrial design, engineering design, production planning, production, sales, maintenance and disposal. Currently, a bunch of methods has been developed in the context of PLM [14, 15, 16]. These methods on the one hand and the methods and theories of the subareas within the lifecycle on the other hand are only loosely connected and lack of integration so far. The aim of applying pattern languages to PLM is to develop a cohesive PLM-theory, which relates current PLM-methods to each other, integrates them with the methods and theories of the subareas and makes the evolving comprehensive set of methods continuously applicable during the whole product lifecycle as an interdisciplinary lingua franca.

4.1 Conclusions from Applying Pattern Languages in Other Disciplines

A common motivation for the application of pattern languages throughout the various disciplines, which is also expedient for PLM, is to capture archetypal knowledge and stimulate a generative problem solution process based on this knowledge. Moreover, from the application in other disciplines some conclusion regarding the application of pattern languages to PLM can be derived. From the application to object-oriented software development the answer to the question, whether it is at all possible to apply pattern languages to PLM, can be derived:

To represent the lifecycle of a product, three models are required [17, 18]: A product data model, a process model and an organization model. The process model defines tasks to generate the data of the product data model. The product data model constitutes the product structure with the integrated product components as well as the properties of the product. The organization model comprises the roles within the company and their structure. Via roles responsibilities for certain tasks are assigned [17]. Gamma, et al. [6] defines three kinds of patterns: Creational patterns, structural patterns and behavioral patterns. All of them are referring to software objects. Because product data is stored by software objects in most systems, the principle of structural patterns is directly transferable to product data models. Creational patterns describe constructs to create software objects. Because product creation processes can be modeled object-oriented [19], the principle of creational patterns can be transferred to product creation processes by referring to the modeling objects via creational patterns. In [19] even an example to model responsibilities is stated. This can easily be extended to an object oriented role model, which can be addressed by behavioral patterns. The role model becomes an organization model, if it is amended by the related organizational structure. Thus, a combination of behavioral and structural patterns will be appropriate to describe organizational constructs. Because all three models, consequentially describing the product lifecycle, can be addressed by pattern languages, it becomes apparent that pattern languages are feasible to be applied to PLM.

A major objective of Alexander's work is to share the knowledge incorporated by the pattern language with the inhabitants (customers) and facilitate them to participate in the design process [4]. For similar reasons pattern languages are applied to HCI design [1]. Users on the one hand do not understand the technical jargon of software engineers and software engineers on the other hand have only a vague cognition of the application domain. Pattern languages are applied to establish communication between both parties. In general, the language-like concept of pattern languages described in the section "Syntax and Semantics" makes this approach capable to become a common lingo, which facilitates collaborative work between experts from different disciplines as well as laymen like customers.

4.2 Applying Pattern Languages to PLM

Current pattern languages for software development only cover a single area and one user group (software developer). Even the pattern language of Alexander covers one area (architecture), but addresses two user groups (architects and inhabitants). HCI-Design patterns span three areas (application domain, HCI, software development [10]) and are related to three user groups (user from application domain, HCI-designer, software developers). PLM comprises even more subareas to be integrated as well as user groups to be addressed.

Fig. 2 depicts a framework for a PLM pattern language comprising these subareas. Dependencies between different areas are represented by overlapping circles. For example, strategies define the operational methods to be applied. Operational methods in turn determine how PLM-supporting systems have to be arranged and configured. This framework divides the area of PLM into three segments: super ordinate strategic approaches, operational approaches to realize value-added chains according to the strategies and approaches to support the effective and efficient progress of value chains. In the strategy-section the strategical goals can be seen as the objects to be designed. The design objects in the operation-section are the products and components, whilst in the support-section the PLM-supporting systems and the design tools are the design objects.

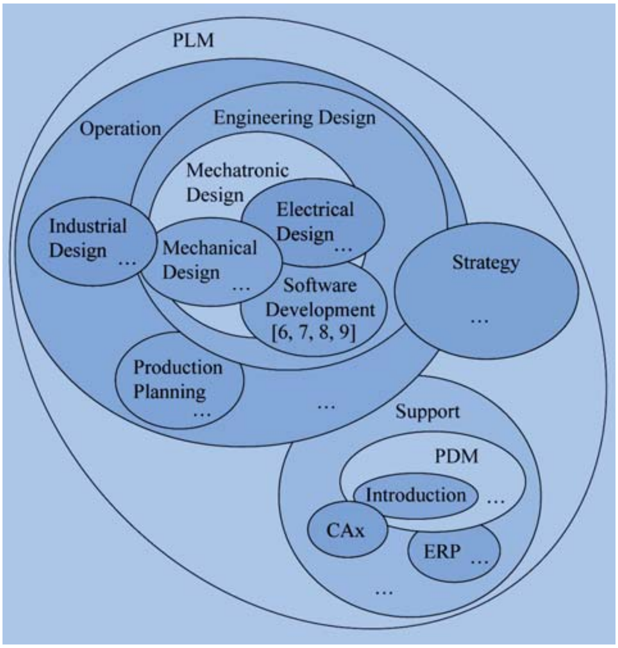

Fig. 2: A framework for a PLM pattern language

To develop a complete pattern language for PLM the grammar of the language has to be developed as well as the structure of a pattern and the contained content. The grammar of Alexander's language structures pattern according to the spatial structure of the addressed design objects, i.e. patterns addressing large-scale objects refer to patterns addressing comprised small-scale objects. PLM is more complex than architecture, because it integrates different kinds of design objects with various levels of details, different lifecycles and various engineering disciplines. Thus, an approach with time as a primary structuring criterion supplemented by the spatial size like proposed in [10] as a secondary one (cp. [10]) seems to be appropriate. Additionally, the design object is required as third structuring criterion. A structuring criterion regarding the involved engineering disciplines is not expedient, because one aim of the PLM pattern language is to create a common interdisciplinary lingua franca.

The inner structure of a pattern proposed by Alexander (section “Syntax and Semantics”) seems to be largely appropriate to be transferred to PLM patterns. The following amendment might increase the usability of the pattern language: In [20] the approach of a context cube was proposed to generate relevant knowledge according to the current context of an engineer (engineering context). Even patterns are associated with a context, which consists of further pattern referring to the original pattern via the “supporting patterns”-reference. This can be seen as the context of the knowledge (knowledge context). To make the pattern language more applicable, the structure of PLM-patterns might be amended by an entry specifying the engineering context, which the pattern is appropriate to be applied in. This will guide the user to express solution ideas according to his current context considering his role in the development process, the tasks he has to fulfill and the engineering object he has to design.

The framework depicted in Fig. 2 gives an overview of the content covered by the PLM pattern language. As an integration approach it comprises not only PLM-strategies and supporting tools, but also content from various subareas within industrial design, engineering design and production planning. The integration of this content makes the development of PLM pattern languages a challenging, but very rewarding mission. Especially the development of sub-languages describing the following topics seems to be particularly interesting: PLM-strategies and their dependencies on the operational level, integration of customers into the design process, collaboration between industrial design and engineering design, mechatronic design (collaboration between mechanical design, electrical design and software development), integrated representation of current approaches in mechanical engineering, collaboration between engineering design and production planning, arrangement and configuration of PLM-supporting systems according to operational approaches, interconnection of PDM- and ERP-Systems and introduction of PDM-systems.

5 Summary and Outlook

In architecture, the pattern approach has not been received well, because Alexander's concept enabled the inhabitants (customers) to influence the design process and take some influence away from the professionals [10]. Obviously, architects were not inspired to apply pattern languages. In contrast, in PLM and engineering design professionals are encouraged by the management to cooperate with customers. Thus, there is some potential for pattern languages to be bruit about in these areas. The example of software development, where pattern languages are already very popular, endorses this assumption.

This paper has accounted for the applicability of pattern languages in PLM and engineering design. Some approaches to develop a PLM pattern language were proposed. Further research has to be done to refine these approaches and actually create the PLM pattern language. These efforts are published at *www.plmpatterns.org*.

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Development of a Strategy Tool for Environmental Compliance Management

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Abstract
The EU environmental legislation restricts the use of certain substances in products and, in addition, sets targets for recovery of products reaching end-of-life (EOL). Little support is provided to producers on how to obtain the best design alternative for their products (meaning the best compromise between cost and environmental compliance). The authors propose a strategy tool based on the Analytic Hierarchy Process (AHP) as a solution to this problem. It will generate information needed to make the decision, will present it in a structured way and will permit the direct involvement of the users.

Keywords
Design for Environment (DFE), Cost Model, Strategy Tool, Analytic Hierarchy Process (AHP)

1 Introduction

With the increasing pressure of environmental legislation [1, 2, 3], the selection of the design and the manufacturing processes which comply with environmental requirements have become evermore complicated and onerous on OEMs (Original Equipment Manufacturers) as well as other players in the supply chain. In electronic or automotive engineering, for example, the goal of the designer is to determine the most cost effective design alternative in order to optimise the environmental compliance of the product, according to the requirements of the WEEE Directive, the ELV Directive and other related environmental legislation [1, 2].

The design and evaluation of products against the criteria demanded by environmental legislation and the cost targets of the company has become an important challenge for companies all over the world [4, 5]. Whilst trade-offs should include parameters such as quality, reliability, environment compliance and cost [6], it is not possible to suggest a precise algorithm to cater to because the solution depends on various factors such as the type of product, legislation or the company policy at that point in time.

The aim of this paper is to propose a decision-support model that can assist product designers in the decision-making process. The proposed model is based on information offered by the DFE Workbench tool presented in section 2, which uses Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies. Section 3 proposes a strategy module to support designers in assessing the environmental performance of their products and their compliance with environmental legislation, as well as their effectiveness and viability such that a balanced trade-off can be made between cost and environmental compliance, leading to affordability and sustainability over the product life cycle.

2 Design for Environment – The DFE Workbench

The development of environmentally superior products (ESPs) represents the most recent obligation placed on designers [7, 8]. In order to design ESPs, the authors developed the DFE Workbench (methodology and tool) which is focused on the analysis, synthesis, evaluation and improvement of the life cycle design of the product.

The DFE Workbench is a CAD integrated software consisting of 3 modules: the DFE module which is strictly related to design for environment, the cost module and the strategy module.

2.1 The DFE Module

The DFE module is a design for environment software tool integrated into a CAD environment (the application has been ported to Pro Engineer 2001, Solid Works 2000 and Catia V5 R16). It has been developed to assist and advise the designer in the development of ESPs in order to meet the requirements of the latest legislation related to environment and the customers' needs. The DFE module consists of (see figure 1): the Impact Assessment System (IAS), the Structure Assessment Method (SAM), the Advisor Agent, the Knowledge Agent and the Report Generator.

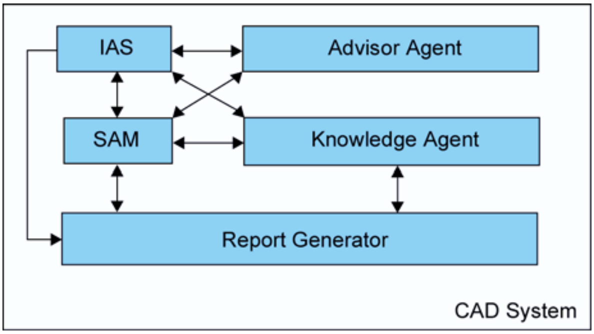

Fig. 1: The DFE module [7,8]

The *Impact Assessment System (IAS)* is an abridged quantitative approach to LCA, performing synthesis, evaluation, prioritisation and improvement of environmental data. It automatically extracts the appropriate data from the CAD drawing. Based on this information and the processes associated with each component, environmental impact may be calculated for each component or for the entire assembly.

The *Structure Assessment Method (SAM)* is a complex methodology, which quantitatively measures and records data such as material compatibility/substitution (taking into account fasteners), components' serviceability, number and types of fasteners, number and types of tools required for disassembly and total standard disassembly times and component removal times.

The *Advisor Agent* has two functions: firstly to prioritise variables generated by the IAS and SAM tools; secondly to give advice to the designer on alternative structural characteristics in order to enhance either the environmental impact or structural characteristics of the emergent design.

The *Knowledge Agent* provides advice to the designer in a consultative mode (for example, help to find a material with specific mechanical and environmental properties).

The *Report Generator* automatically generates reports on the product designed by the user. Using the DFE module, several design alternatives can be generated according to the designer's choice or the suggestions made by the tool's advisor in order to improve the environmental characteristics of the product. IAS and SAM will calculate all indicators for each alternative. Design parameters that can be changed and that influence the product's impact on the environment as well as on costs include: type of material, mass, dimensions, no. of fasteners. Any change to these parameters can result in different processes which will result in a modification of the environmental impact and the total cost of the product.

2.2 The Cost Module

The Cost module models various costs associated with the product life cycle (see figure 2). It offers the designer a support tool that gives indications of the product's cost and also permits comparisons of design alternatives at the early stages of the design.

The cost model is a combination of life cycle costing (LCC), feature-based costing and activity-based costing (ABC). It aims to give the designer a complete picture of the product cost and to show the influence of different changes in the design on the total cost of the product. To effectively compare alternatives, the designer must be able to accurately estimate costs for the complete system so that 'what if' scenarios can be built.

The output of the Cost module is intended to give the designer a summary of the costs of the entire product life cycle: production cost, use cost, end of life (EOL) cost and environmental cost, all of which will be used by the Strategy module.

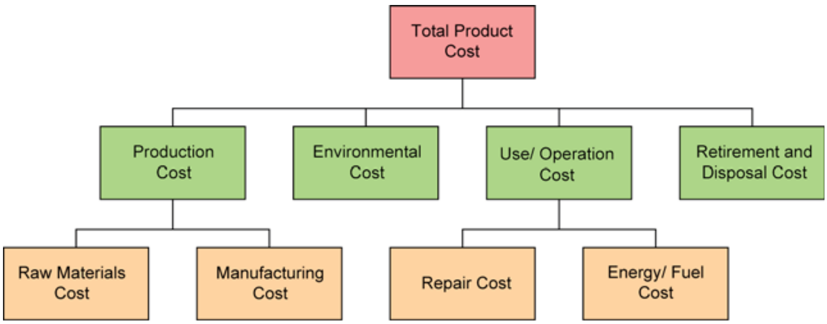

Fig. 2: Cost breakdown structure

Production Cost

The production cost of the product is calculated using the ABC method [9]. The methodology is extended by using feature-based cost estimation in coordination with ABC (consumption of cost centres depends on the design parameters). This allows the designer to evaluate the product cost based on physical properties very early during the product design stage.

Environmental Cost

The model takes into consideration only the internal environmental costs related to the product which represent environmental costs that have a direct financial impact on the company (such as waste and emissions treatment cost, labelling cost, licence and permit fees).

Use/operation Cost

The costs categories considered in the cost model for the use/operation phase are repair/maintenance cost and energy/fuel cost. Design parameters such as Mean Time to Failure (MTTF) for unrepairable components and Mean Time Between Failures (MTBF) for repairable components are considered in the repair cost model. Depending on the type of product (energy consuming or fuel consuming), the energy cost or fuel cost is modelled for the entire product lifetime.

EOL Cost

An EOL option is defined for each component of the product and costs associated to that particular option are modelled.

3 The Strategy Module

The consideration of environmental criteria in the product design process can often lead to conflicts when it comes to the economical evaluation of the product design [6]. Consequently, it is important that compromises be found between environmental criteria and economic criteria. Such compromises can only be found by considering the need to respect the environmental objectives of the company, national and/or international environmental policies and legislation [1, 2, 10], in addition to economic constraints (costs).

The Strategy module addresses this compromise situation. It uses the Analytic Hierarchy Process (AHP) [11, 12, 13] for multi-criteria decision-making in the selection of a design alternative. The decision situation involves the consideration of variables which can be easily quantified into monetary units, as well as those environmental aspects which cannot. Therefore the decision-making process can be influenced by multiple criteria analysis and evaluation.

3.1 The Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) was developed as a methodology for multi-criteria modelling and decision-making [11, 12]. It provides a framework for facilitating a systematic approach to decision analysis that can integrate and incorporate the values of the decision-makers and legislative constraints with technical information in order to examine the overall implications of each alternative [14].

AHP provides a hierarchical framework within which multi-attribute decision problems can be structured [11]. AHP is not a substitute for decision-making; it makes complex decision processes more rational by synthesising all of the available information about the decision in a system-wide and systematic manner and helps the designer prioritise the criteria in a manner that otherwise might not be possible [15].

3.2 The Strategy Module for Support of Decision-Making at the Design Stage

The challenge to the authors was to construct a strategy tool which included all relevant environmental and economic criteria and which could be applied to decision-making at the product's design stage. The goal was then to choose the design alternative which satisfied best all of the environmental and economic criteria. The AHP methodology was chosen for this purpose. Figure 3 shows the decision tree used by AHP to solve the design alternative selection problem.

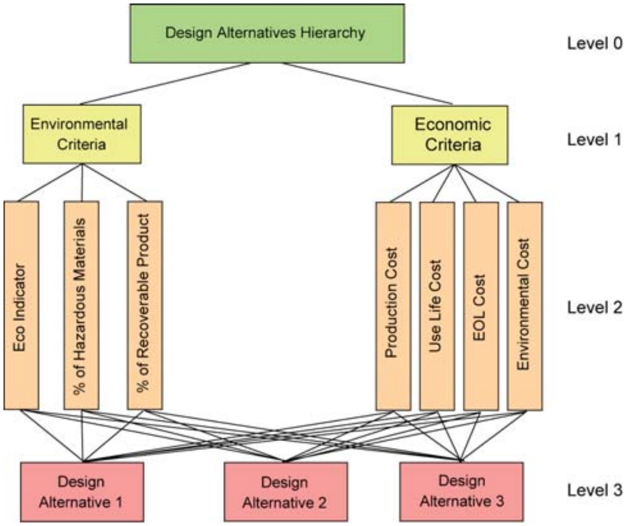

Fig. 3: The hierarchical structure used in decision-making for design alternatives

Once the hierarchical structure is defined, *pairwise comparison judgements* are made. An important feature of the tool is that it permits the direct involvement of the designer, which is very important considering that companies differ in the criteria they consider important according to the type of business and ownership of their product (e.g. leasing) and the product's life cycle (see figure 4).

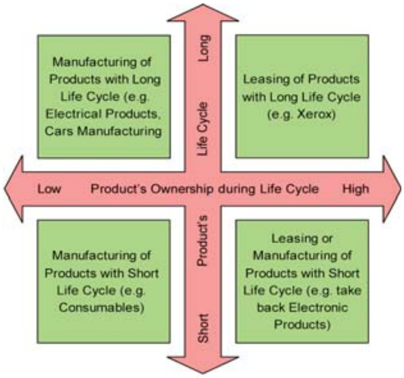

Fig. 4: Company types based on product's life cycle and ownership

The decision-maker (i.e. the user of the tool) compares each criterion to those that have the same parent node. According to the position of the company in the diagram in figure 4, indicators in the hierarchical structure (environmental and economic) will have different importance for the decision-maker.

Pairwise comparison matrices are then formed. Table 1 shows a matrix of pairwise comparisons of the criteria at level 1 in the decision tree with respect to the overall objective, i.e. obtaining the best design alternative. Criteria in rows (*i*) are scored against criteria in columns (*j*).

Tab. 1: Example of matrix of pairwise comparisons of the criteria at the first level in the decision tree with respect to the overall objective

i \ j	**Environmental criteria**	**Economic criteria**
Environmental criteria	1	7
Economic criteria	1/7	1

The diagonal values of any pairwise comparisons matrix are always 1 as each criterion is compared with itself. The lower triangular part of the matrix contains the reciprocal of the values in the upper triangular part ($a_{ji}=1/a_{ij}$).

The next step is obtaining the *relative importances of criteria and alternatives* using the eigenvector method. Let us denote the pairwise comparisons matrix as $A=(a_{ij})$. If n criteria ($C_1, C_2, \ldots, C_n$) at the same level are compared, then the relative weights are the normalised elements of the eigenvector $w=(w_1, w_2, \ldots, w_n)$ which verifies the equation:

$$(\lambda_{\max} I - A)\, w = 0 \tag{1}$$

where λ_{max} is the largest eigenvalue of A

In practice, to determine the relative weights the sum of each column will be made. Then each number in the matrix will be divided by the sum of the column in which it appears. By averaging across each row, the final relative weight is obtained for each criterion.

Let us denote the relative weights derived from pairwise comparisons of the criteria at level 1 as:

$$w_i, \text{where} \sum_{i=1}^{2} w_i = 1 \tag{2}$$

and $i = 1, 2$; i = criterion at level 1

The relative weights derived from pairwise comparisons of the criteria at level 2 corresponding to each criterion at level 1 are:

$$v_{ji}, \text{where} \sum_{j=1}^{n} v_{ij} = 1, \forall i, i = 1,2 \tag{3}$$

and i = criterion at level 1

$j = 1, 2, \ldots, n$

j = criterion at level 2 corresponding to criterion i at level 1

n = number of criteria at level 2 corresponding to criterion i at level 1

The relative weights derived from pairwise comparisons of the alternatives at the bottom level with respect to each criterion at level 2 are:

$$V_{kl}, where \sum_{l=1}^{3} V_{kl} = 1, \forall k, k = 1,2,\ldots,m \tag{4}$$

and $l = 1, 2, 3$; l = alternative

k = criterion at level 2

m = total number of criteria at level 2

Once all the eigenvectors have been obtained, the *process of synthesis* can proceed. The absolute importances of criteria at level 2 corresponding to each criterion at level 1 will be obtained with the formula:

$$U_{ij} = w_i v_{ij}, \forall, i, i = 1,2; \forall j, j = 1,2,\ldots,n \tag{5}$$

where

i = criterion at level 1

j = criterion at level 2
n = number of criteria at level 2 corresponding to criterion i at level 1

Let us denote the absolute importances of criteria at level 2 calculated before as:

$$W_k \tag{6}$$

where $k = 1, 2, \ldots, 7$
k = criterion at level 2

Then the scores of the alternatives (design alternatives) are:

$$S_l = \sum_{k=1}^{7} V_{kl} W_k, \forall l, l = 1,2,3 \tag{7}$$

where l = alternative
k = criterion at level 2; $k = 1, 2, \ldots, 7$

The scores of the alternatives will give the hierarchy. The best design alternative is the one with the highest score, max S_l.

4 Conclusions

Increasingly, the product designer's task is made evermore complex due to the legislative pressures and increasing consumer environmental consciousness, in addition to other factors (i.e. technical and economic).

In addressing this situation, the authors proposed the DFE Workbench which includes a strategy module for decision-making at the design stage. Based on AHP, the strategy tool supports the designer in structuring and evaluating different alternatives. It incorporates environmental considerations and constraints stated by legislation and the 'voice of community' in the decision-making process along with economic judgements which can alters the product design decision. The main advantage of the strategy tool from the decision-maker point of view is that he/she is directly involved in the process and the result of the assessment is based on his/her judgement.

In conclusion, the DFE Workbench comprising the DFE Module, the Cost Module and the Strategy Module, represents an integrated solution to the design of environmentally superior products.

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Software Engineering and Knowledge Engineering: From Competition to Cooperation

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Abstract

The development of engineering systems is usually based upon the deployment of classical software engineering (SE) lifecycle (LC) models. In the case of Knowledge integration in Knowledge Based Systems, specific knowledge Management cycle, often called knowledge engineering (KE) lifecycle, is adopted.

The objective of this paper is to discuss the relations between the software engineering lifecycle and the knowledge engineering lifecycle. Assuming that deployment of SE deals with the identification of the application components, KE tends to define the content of these components. However, these two cycles are deployed separately. The consequence is a lost of expertise in the final software solution. The goals of our study are to minimize this expertise loss by identifying the correspondence between the activities of the two cycles and to propose a common lifecycle for both SE and KE within the same system development project.

Keywords

Knowledge engineering, Software engineering, Knowledge processing

1 Introduction

The experience of the whole product lifecycle has shown that decisions about product development are made continuously during the development cycle. To enhance the communication within organizations, a general reference system is needed to make the concurrent engineering easier [3]. During product development, designers often juggle with many, and often conflicting, constraints to balance aesthetics, manufacturability and functional objectives within a marketable product specification [7]. In order to help engineers in managing this information flows, software systems nowadays tend to replace the user in performing routine tasks. Nevertheless, software development has been acknowledged as a complex problem-solving activity done in a multi-dimensional space. People actively involved in software development need support in understanding and documenting not only the description of the software developed, but also the problem domain and the reasons behind decisions taken during evolution [17]. Development methods do not provide such support, and researchers begin to explore the integration of reasoning in specific phases of software's development. In this sense, organizations have understood that, one strategy to be competitive is to exploit and reuse their experts' intellectual assets. Most of them are now investing on this capital reuse by setting up engineering activities that focuse on the capture and the management of this experts' knowledge. This moves the systems from being information based to knowledge based. The difference is that the system contains the context of use of the data and information. The new generation of engineering systems is called knowledge-based systems (KBS). Such systems are software programs designed to capture and apply domain specific knowledge and expertise in order to facilitate problems solving. A Knowledge based system can be defined as a computerised system that uses knowledge about some domains to arrive at a solution to a problem which should essentially be the same as the solution concluded by a person knowledgeable, about the domain of the problem, when confronted with the same problem [10]. However, during the development of such systems most organizations find it necessary to use different lifecycle models for different projects, depending on the nature of the project: software development or knowledge integration.

The objective of this paper is to discuss theses separations in order to put in parallel the activities related to each aspect of the system, and to identify the correspondences between them. The first section introduces some established distinctions between SE and KE to illustrate how the two disciplines switch from a competition to cooperation. After that, the lifecycle models proposed in both engineering are presented. The forth section presents a synthesis to allow the identification of the correspondences between the two lifecycles. Our analysis focuses on the engineering activities structuring during the development of the KBE application. The questions are: should we set up two different projects to develop a KBS/KBE system? How to deploy the two lifecycles within the same project? What is the knowledge processing we should set up at each stage of the software application development? At the end, we will propose an integration of knowledge engineering activities within the software lifecycle to allow a development of such applications using a common and a single lifecycle.

2 Software Engineering and Knowledge Engineering

Software Engineering and Knowledge Engineering are increasingly converging into a common and a single lifecycle, as the two engineering disciplines are studied in more depth, and increasingly larger systems are developed in the two fields. Software engineering was created to provide computable solutions to real-world problems. Knowledge Engineering, on the other hand, is a fruit of the postindustrial society, with a switch from the need for manpower to the need for brainpower or, to put it differently, from manufacturing to mind-facturing [2].

A major debate has begun in the 1990's on SE and KE. Some authors consider them as two completely different branches of engineering, while others point out similarities in their development [1]. Kierulf and colleagues [12] clearly established the differences between SE and KE. These differences have sometimes led to a separated deployment and application of these two branches of engineering with the belief that they were mutually exclusive disciplines. Software engineering processes have traditionally been used to develop technical products to meet a client's requirements. Requirements are considered to be a different thing from "needs", and "solutions" are considered to be a different thing from "products" [16]. SE's intent is thus to tightly control the system development process so that the products that are delivered at the end match what was originally thought to be required. The SE and KE concepts are introduced in the next sections as well as the existing lifecycle models in both disciplines.

3 Software Engineering Models

The term of Software Engineering appeared in 1960's to characterize the formalization of an engineering approach for software development. The aim was to identify, classify, and discuss the problems with large-scale software production in search of a solution to what was referred to as the "software crisis" [18]. There are various definitions of SE LC. It can be defined by being series of steps through which the product development progresses. However, differences still exist for the definition of SE. SE to day is understood as the application of tools, methods, and disciplines to the production and maintenance of automated solutions to real world problems [5]. Farther, Blanchard [4] described it in considerable depth.

A SE LC model is a view of the activities that occur during the software development. It describes phases of the development cycle and the order in which those phases are executed. Davis has identified the main benefits of SE LC model [8]. Typically, the LC model includes: requirement analysis, design, construction/implementation, testing (validation/verification), installation, and maintenance. According to this LC, several models exist and each company adopts its own model, but all have very similar patterns. The next paragraphs present briefly some of these models.

3.1 General Model

The general model is the basic model used for SE development (see Fig. 1). It is composed of four major phases, and each phase produces deliverables and guidelines required by the next phase in the whole LC. Starting from the software requirements defined for the design phase, and driven by this design code is produced during implementation. Testing verifies the similarities between the deliverable of the implementation phase and requirements.

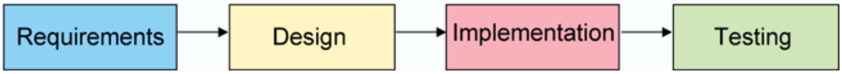

Fig. 1: General lifecycle model

This model uses to work well for smaller project where requirements are very well understood. It offers the advantages of being simple, easy to use and to manage, and its phases are processed one at a time and each one produces specific deliverables. Nevertheless, using this model in large project and new domains is not recommended because, it can lead to a high amount of risk and uncertainty, and thus kill the project.

3.2 Waterfall Model

The waterfall model is one of the first models developed. Winston Royce [18] proposed it in 1970 to describe software development. Later, it serves as a building block for most of the proposed lifecycle models. Like the general model, the waterfall model views the whole software development process as a sequence of phases and each phase has a set of goals and activities that need to be accomplished.

Differently from the first model, with this one the development progress can be seen as flow from one phase to another with possible feedbacks to the previous phase. This, a priori, implies that there are no constraints, which impose that activities from the current phase should be done only in that phase. Adding to that, a complete cycle of execution of all the phases might lead either to the complete system or just a part of it, depending on detailed level of requirements.

3.3 The V Lifecycle Model

Like the previous models, this one begins with the identification of software requirements and ends with the formal validation of the developed software regarding those requirements. The software development V LC model consists in a sequential execution of processes with possibilities of keeping track of the overall project progress. It describes the activities and results that have to be produced during software development. The V LC model defines in a first part the system specification activities. Then it sums up the testing steps to validate the developed solution regarding the specifications. The keystone of this model is the development stage. The V lifecycle is suitable for projects that have well-defined requirements that are unlikely to change significantly over the life of the project. Within this model, the requirements are listed. They have to be traced during the design of the system. At the end, they verify the complete and correct implementation of requirements. Since everything is well defined, this type of approach can be carried out under a controlled context.

Besides these three well-known models, other models have been proposed and reused several time as well in the literature as in the industry. Among these models we can mention the incremental model, the spiral model, prototyping, etc.

3.4 Conclusion

According to Davis [8] each model is not particularly different, but they all provide different views of the same basic software development process. Although each LC model has its own views to develop software, generally models are more complementary than exclusionary. All the SE LCs serve as tools to monitor the activities and overall progress of software development focusing on the system's structure. However, new systems generation tend to face the market evolutions and challenges by developing systems based on experts' knowledge. The problem is that SE does not take into account the content of the system in terms of data, information and knowledge to be manipulated and/or generated by the system.

This problematic led to the definition of new engineering activities, called Knowledge Engineering and Knowledge Management (KM), to allow the integration of knowledge within computerized systems. The KE concept is presented in the next section.

4 Knowledge Engineering Lifecycles

Nowadays knowledge management attracts more and more attention in either research or industry. Organizations often spend a lot of time and money to launch strategic KM initiatives without first assessing whether or not their culture is mature enough for the implementation of such initiatives.

Indeed, customers usually encode the knowledge related to their requirements, into text, drawings, or verbal messages. The main disadvantage of this form of knowledge is that it evades critical discussions [15]. Knowledge management means attending to processes for creating, sustaining, applying, sharing and renewing knowledge to enhance the company's performance and create value for that company [17]. While knowledge engineering represents the engineering discipline that involves capitalizing and integrating knowledge into computer systems in order to solve complex problems normally requiring a high level of human expertise [19]. Various definitions of KE have been proposed; these definitions focused on three fundamental elements: people, processes and technology. All three of these elements complement one another and they are critical to the successful implementation of a KM and KE program. In this paper the existing methods will not be approached (for an overview see Dieng & al. [9]), only some KE lifecycles will be introduced.

The most known KE LC model is the one proposed by Grundstein [11]. This model processes knowledge in four main phases. The first one consists in identifying, and localizing relevant knowledge as well as its potential sources. The second phase, deals with the extraction of the identified knowledge from its sources, and to structuring it for an integration objective. The development phase consists in spreading the knowledge, through the system, in such away that every one can use it. However, reusing knowledge by different users sometimes can lead to contradictions, that is why the forth phase is necessary to ensure the coherency and updating within the system and the organization. From a knowledge management point of view, Grundstein proposes to define another phase called management phase in order to manage, control and coordinate the activities of the overall LC.

Candlot introduced a Knowledge lifecycle for KBS/E [6]. This LC introduces high-level activities for knowledge processing while developing knowledge based engineering system. These KE activities are gathered into two distinct phases: Infrastructure identification and Architecture definition. The proposed LC allows system infrastructure identification in four mains steps:

- Identification: as its name indicates it, the purpose of this step is to identify all the concepts used within the specified domain.
- Extraction: it consists in recovering and analyzing the concepts identified in the previous step. Existing associations between concepts are also highlighted.
- Structuring: its objective is to organize domain infrastructure semantically.
- Formalization: in this step, the semantic concepts are represented syntactically to allow domain architecture definition.

Otherwise, during problem solving, domain's infrastructure and architecture evolve and thus their states change. The different states will constitute the infrastructure of the system, and the transitions from one state to another will allow the system architecture construction. To allow this construction, the LC introduces four steps:

- Refinement: to validate among the formalized concepts the most relevant ones regarding the problem that has to be solved by the system.
- Development: formalized concepts are translated in terms of classes and attributes to generate development code.
- Diffusion: it consists in putting the system at the disposal of the user to check if it corresponds to the initial specifications and requirements.
- Maintenance: its aim is to keep the system as coherent as possible through its utilization. It is thus necessary to specify procedures to allow knowledge updating.

However, the proposed lifecycle does not take into account the system development. It objectives are to specify the content of the system in terms of knowledge as well as its utilization.

The existing methods, models and LCs for KE focus on the knowledge capture and formalization during KBS/E development. This means that, for developing such systems, two LCs are required. The deployment of two LCs within the same system development project can lead to redundancies, especially during requirements gathering and system design. In order to minimize the potential redundancies we propose to integrate KE activities within a V SE lifecycle.

5 SE and KE: Towards a Common Lifecycle

One of the primary challenges facing KE in large scale systems development is finding a way to optimize the use of products generated as a result of the KE process. Many systems employ different software solutions for engineering problems and then try to integrate them through a user interface (example of CAD/CAM systems). Unfortunately, the expert may not be available immediately to attend to the problem, or the organization may not even have a competent expert for every problem that may arise [4]. Adding to that, decision makers who don't understand the basics of software engineering change the target continuously without looking at resulting costs and delays. To manage this problem, KE tends to establish guidance and structure flexible enough to support evolving and changing requirements from multiple end-users.

Based upon the coupling of the V lifecycle and the KE lifecycle proposed by Candlot [6], we propose a knowledge based software development lifecycle (Fig. 2) witch support evolving and requirements changing from multiple experts. This LC is composed of two distinct phases represented by the two parts of the V LC. The first part, called characterization activities, gathers all the activities concerning system specification and design. The second one, automation activities, gathers activities related to the integration and validation of the system. We started with the idea that, to develop any kind of software, we need to completely understand the problem and problem user domain, its requirements, available solutions and new solutions to be automated. However, developers do not and could not have a complete understanding of problem and user domain. Their objectives are to understand what the system should perform and how the user can interact with it. But, they will not pay the same attention to the knowledge that they have to integrate into the system since the knowledge is not written down in form of specifications. What we are proposing is to offer a possibility for both developers and knowledge engineers to work collaboratively within the same project by distributing development tasks among them. The proposed LC will also permit to manage late requirements changes without affecting developers' work. To reach these two objectives, we organized KE activities trough the V LC.

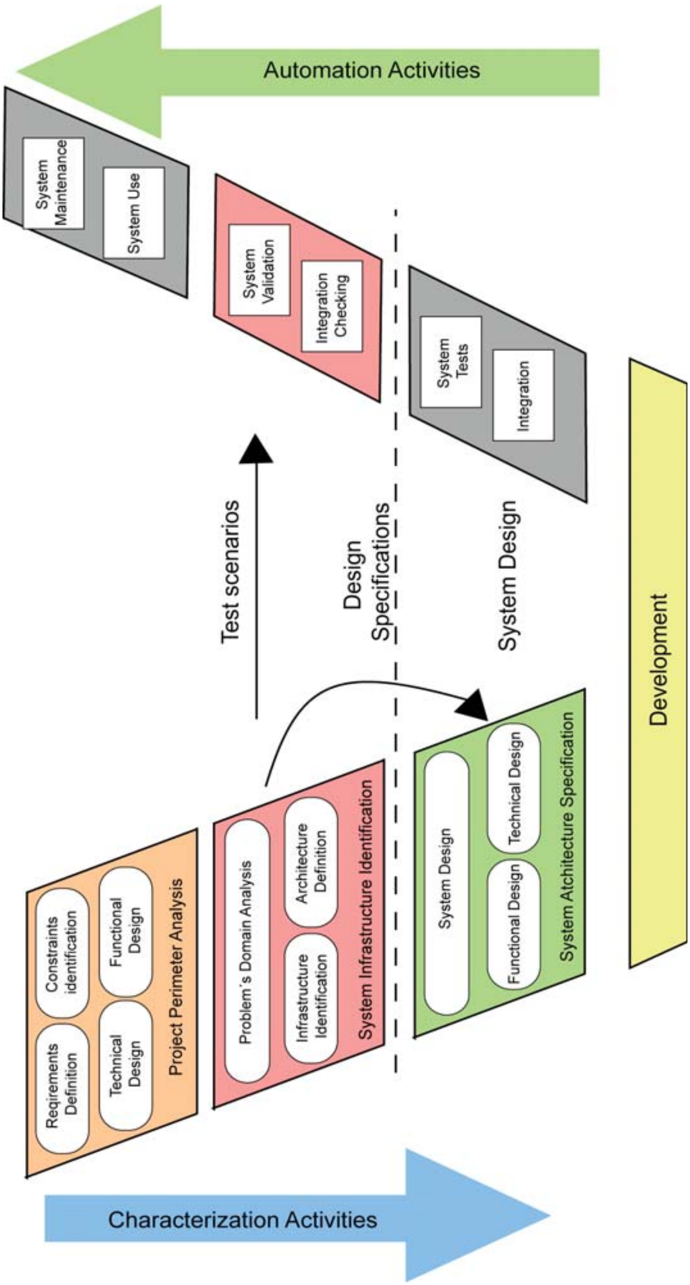

Fig. 2: KBS development LC

5.1 Characterization Activities

Characterization activities consist of three main steps: project parameter analysis, system infrastructure identification and system architecture specification. Each step is composed of sub steps aiming at specifying a certain aspect of the system.

Traditionally, the analysis focuses particularly on what are the functionalities to implement so that specified requirements will be satisfied. However, the existing reasoning behind these functionalities is not captured. Thus, to increasing domain understanding for developers unfamiliar with portions of the domain, the Infrastructure identification phase of KE LC is deployed to organize domain functions, data, information and knowledge associated with task performers in the domain (its steps have been described in the previous section).

Introduced between project parameter analysis and system design, the infrastructure identification aims to determine the different states of the used concepts during problems solving as well as their interdependencies. The next step which is system architecture definition aims to trace the evolutions of the infrastructure elements and thus identify existing links between them for designing the system. This step reinforces the high-level design phase of the V LC that focuses on system architecture and design. At the end of these steps, the system development specifications are established. Developers will then translate them on classes, attributes, functions, and procedures, and so on to develop the system. The development step is where all coding takes place. Once coding is complete, the path of execution continues up the right side of the V where the test plans developed earlier are now put to use.

5.2 Automation Activities

This part of the V LC gathers the activities related to the integration, test, checking, validation, use and maintenance. Since these activities follow the development step, knowledge engineering activities do not intervene as much that in the left side. In fact KE are needed at the step of checking if all the specifications and requirements have been taken into account. Comparing the integrated concepts and developed functions with the ones identified during previous steps can allow and support this checking. This comparison will also provide a feedback on the project management on one hand, and identifying the gaps between the requirements and the developed system on the other hand. The final validation will be complete if the results of testing correspond with the expected results from the defined scenarios.

Other criteria can be considered for the validation of the system. For example, are the displayed results the same that the results expected by the end user? If not where could the user find explanations? Is the user interface easily usable? Once the system validate, it will be introduced within the organization so that users can use it, give a feedback on it and enrich its contain.

6 Conclusion

To support developers in efforts to implement systems that satisfy domain requirements and highlights the relationships between domain functions and data selected for implementation, this paper proposes a coupling of knowledge engineering and software engineering lifecycles to support and improve knowledge based systems development. The proposed process is based upon the SE conventional V LC and the KE LC proposed by Candlot [6]. The V LC has been selected among other LCs for being the most well-known and used model, and the KE LC for being oriented to knowledge integration. Following an analysis of the LCs proposed in both disciplines, common global objectives and similar steps have been identified. Our objective thus, was to put in parallel the two LCs and identify witch knowledge engineering activities support and completes software engineering. These activities are rearranged to describe system development strategy with the distinction of the system infrastructure step from system architecture step. Such process will allow project manager to manage possible late requirement changing in the system architecture specification during the refinement step. However, this process does not provide guidelines for experience feedback interactive integration. Such solution must be thought to allow effective system maintenance and a continuous knowledge updates.

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Applying KBE Technologies to the Early Phases of Multidisciplinary Product Design

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Abstract
State-of-the-art tools and strategies applied in the early phases of product design offer tremendous benefits for businesses dealing with complex engineering processes – in terms of cost, time to market and product innovation. However, the early design phases are not only inherently complex; by definition, design goals are often loosely-defined and subject to frequent changes. With this in mind, the ideal software for supporting these critical process phases combines automation power with outstanding flexibility, user interaction, transparency and team collaboration options. This paper presents the Pacelab Suite, an integrated software environment specifically developed to support multidisciplinary design investigations. Central to the Pacelab approach is the use of a consistent object-oriented data model and knowledge based working techniques in capturing, formalizing and applying engineering knowledge.

1 Introduction

The ever increasing complexity of products and systems, reduced time to market, shorter product life cycles and highly competitive global marketplace are the most critical challenges the engineering industries are facing today. To stay abreast of rapidly evolving market requirements, it is crucial for engineering enterprises to take the right design decisions early in the product development process. The design of highly-engineered products such as aircraft, automobiles and other vehicles or components can be divided into three distinctive phases: conceptual, preliminary and detailed design. Conceptual design can be defined as the tentative exploration and validation of a set of promising design ideas, proceeding from a given set of high-level business requirements for the future product or system.

During the preliminary design phase, the product is sized, and analytical and trade-off studies are performed to optimize and refine the design approach. Preliminary design typically hands over to the detailed phase where the selected concepts are further scrutinized and specified.

Decisions made in the conceptual and preliminary design phases have a significantly higher impact on the success of the product development process as a whole (in terms of development cost, product quality and innovation) than those made in subsequent phases. This is because these phases determine whether engineering teams can enter the subsequent phase with a small set of high-quality design options unlikely to generate extensive reworks and iteration loops during detailed design, to say nothing of the prototyping and production phases.

Fabrycky and Blanchard (1991, 1999) estimate that more than 60% of the total life cycle cost is committed by the end of the preliminary design phase.

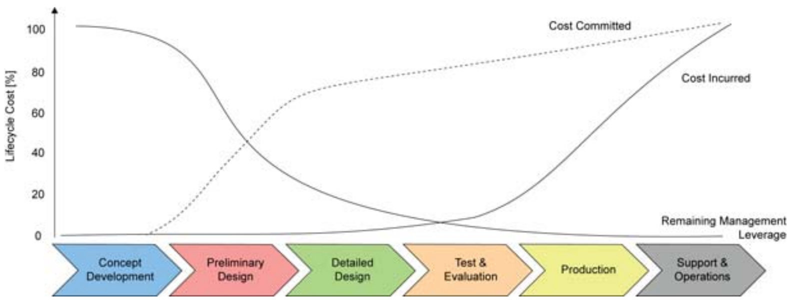

Fig. 1: Life cycle cost committed (adapted from Fabrycky/Blanchard 1999)

However, sound decision-making in the early phases of the product development process is exceedingly difficult since many hard-to-predict factors need to be taken into consideration. Despite the inherent uncertainty, design investigations should by all means:

- Supply a reliable approximation of the final product characteristics
- Consider the entire spectrum of feasible product options including those from off the beaten track
- Regard the product or system as an integrated entity rather than only focusing on individual components
- Ensure technical feasibility by taking into account known methods and constraints from multiple engineering disciplines (which can be as diverse as technical, certification, environmental, cost requirements, etc.)

This complex set of requirements must also be completed within a reasonable time and cost frame, bearing in mind the decreasing life cycle of today's products and omnipresent cost pressures.

A holistic, truly multidisciplinary approach is imperative to successful conceptual and preliminary design since early concepts are better qualified and validated if synergies between individual disciplines are exploited. Ultimately, the integration of individual disciplines provides a sizeable contribution toward optimizing the overall design, or in other words: an optimal design is more than the sum of optimal individual components.

Engineering design is typically performed by several de-centralized teams which are frequently organized according to disciplines and/or individual components of the system being developed. These teams can be located in different departments or even different countries. Multidisciplinary design work therefore requires efficient collaborative techniques and means of sharing information.

While it must be possible to change the focus and granularity of the investigation to meet domain-specific demands, keeping a well-balanced picture of the system as a whole is crucial to steer clear of neglecting certain aspects or disciplines in favor of others. A typical example is over-focusing on geometry or falling prey to a part-centric approach, which prevents engineers from regarding the system's capabilities as a whole. The danger of isolated investigations is, of course, compounded if the project crosses department boundaries.

La Rocca and van Tooren (2006) use the image of the design cube to illustrate the three-dimensional nature of all design investigations: firstly, across the consecutive design phases, secondly from various discipline-specific perspectives and thirdly on different levels of granularity.

The chance of finding the optimum solution for a given set of requirements obviously increases with the size of the design space explored. The design process, however, is inherently iterative; without the assistance of a dedicated software environment, a large portion of the design cycle time has to be spent on time-consuming, repetitive activities. As a result, fewer design iterations can be performed than actually necessary, fewer "what-if" scenarios can be investigated and many potential product configurations and variants must be discarded a priori.

But creativity in design is not only reflected in the range of alternatives considered, but also in the way in which optimum solutions are identified. Design choices seldom afford simultaneous optimums in all key parameters. Finding a reasonable balance in trading off competing parameters therefore frequently becomes more important than optimizing a single variable.

In view of these very specific requirements in the early design phases, an exhaustive exploration of the multidimensional design space calls for a sophisticated software environment that goes beyond the mainly feature-based CAD systems generally employed in this area today.

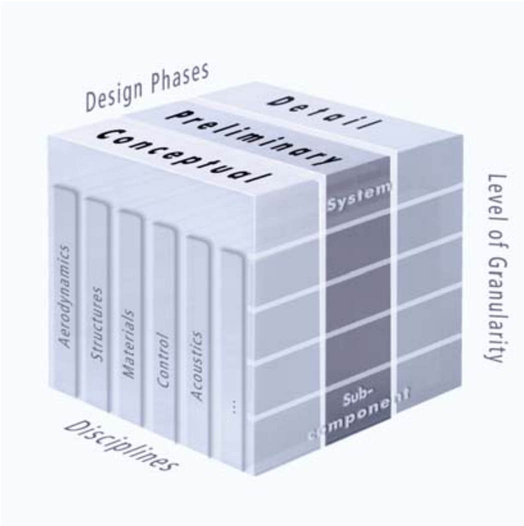

Fig. 2: Three-dimensional design space (adapted from La Rocca/van Tooren 2006)

2 KBE in the Early Design Phases

The proposed solution Pacelab Suite draws on the specific technological capabilities of knowledge based engineering (KBE) to support the early phases of the product development process. KBE aims at computerizing the workflows and activities in the life cycle of industrial products ranging from design to manufacturing and beyond.

The most distinctive characteristics of KBE are the efficient modeling and standardization of corporate product and process knowledge and the rule-based automation of iterative activities and repetitive routines using a high-level programming language. In the realm of design, KBE can be employed to support a wide range of product design functions, applying formal design rules and constraints and leveraging a company's design and manufacturing experience.

In the Pacelab Suite, the workflow is divided between three interoperating applications that provide designers with dedicated tools for the capturing, management and implementation of engineering knowledge.

Presented below is a detailed discussion of the Pacelab approach to knowledge modeling, engineering task definition and multidisciplinary optimization and its benefits to the design process as a whole. The Pacelab Suite is a mature product that has been successfully launched in the aerospace industry and various research institutions; prototype applications are currently being developed in the automotive industry.

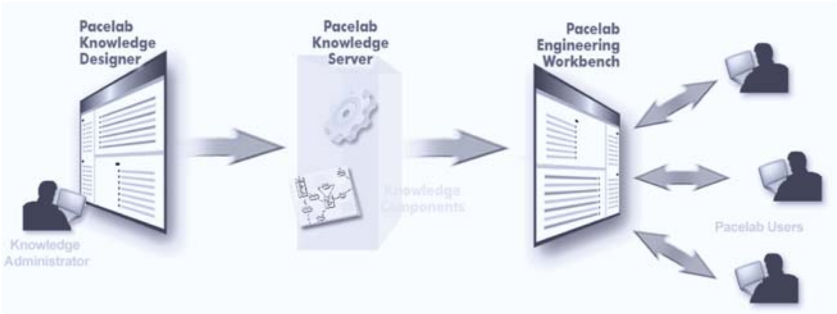

Fig. 3: Capturing, managing and implementing design knowledge with Pacelab

3 Capturing Multidisciplinary Design Knowledge

Although complex products such as aircraft or automobiles come in a great variety of shapes and forms, most, if not all variants of a given product are constituted of parts that share certain functions and behaviors.
Therefore, the Pacelab knowledge modeling approach centers around the concept of breaking complex, abstract design knowledge down to more generic entities, which can be maintained centrally and then reapplied to new or changing design contexts.

The creation of knowledge components is performed in a graphical authoring tool designed to incorporate highly diverse knowledge aspects derived from various engineering disciplines and accommodate them in a unified, consistent system. Based on KBE technology, the tool combines CAD-quality feature-based modeling capabilities with object-oriented programming, enabling the usage of complex calculations within formulas. Geometric and non-geometric parameters can be captured within the same parametric model, which actively encourages both types of parameters to be considered simultaneously when the component is used in a design study.

Knowledge components typically consist of:

- Engineering product data models which represent the engineering components and their subassemblies in a hierarchical structure. Each of these objects is described by a parametric model constituted of parameters and formulas declaring relations between the former.
- Algorithmic knowledge which includes analysis methods, design strategies and constraints. Analysis methods enable complex mathematical calculations to produce numerical results or to change the size, position or other properties of an object. Design strategies allow adding, modifying, shifting, or removing components. Both analysis methods and design strategies can act on individual components or on a more global level. Constraints represent known technical, economic, certification or other industrial limitations.

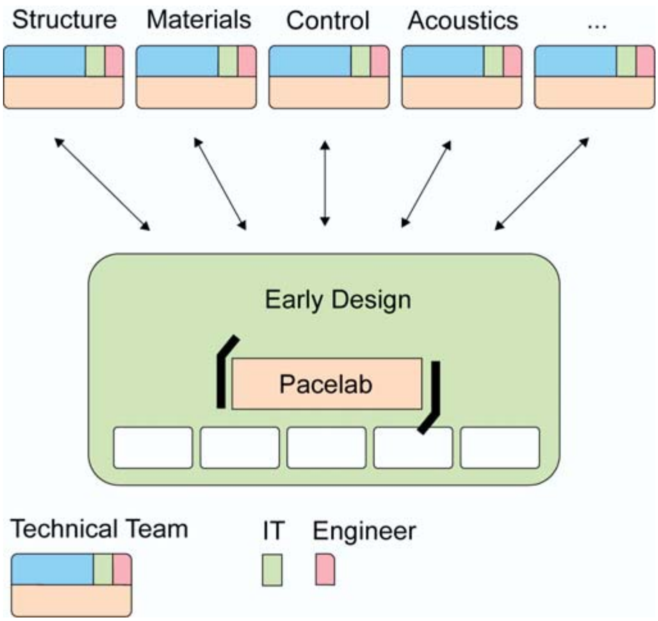

Fig. 4: Knowledge distribution in a multidisciplinary environment

Published to a centralized repository, knowledge components are readily available to design engineers to rapidly build specific engineering tasks. As design knowledge evolves, new components can be added to the repository, while existing components can be redesigned at short notice. Moreover, concurrent access to the data further encourages multidisciplinary collaboration, while allowing the data ownership to remain within the respective disciplines.

4 Defining and Solving the Engineering Task

The engineering task is defined by setting up a case-specific engineering model and determining the objective of the current design investigation. To set up the engineering model, the designer selects suitable predefined components in the required quantity from the central repository and specifies the relations between them. Component selection is mainly dependent on the granularity of the investigation and the design aspects and constraints to be considered.

By thus composing a system of parameters connected to one another through a system of equations, the user implicitly creates a mathematical model which will be used in the resolution process. The mathematical system is represented in a graphical format to keep even the most complex parameter dependencies transparent and manageable for the designer at all times. Impact and computation views allow a detailed study of which parameters are affected by a given input variable and which parameters affect a given output variable.

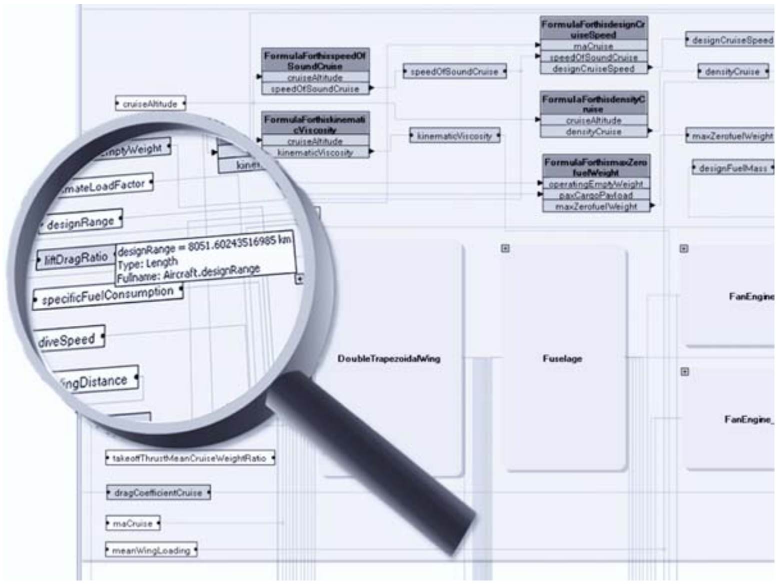

Fig. 5: Graphical representation of the mathematical system

The designer can freely determine the overall objective of the engineering task (and, with that, the solving direction) using a strictly declarative approach, i.e. specifying which are the known input parameters and the outputs to be calculated. The software conducts a combinatorial analysis of the mathematical system and creates a resolution plan identifying the optimum computation strategy for each unknown output parameter. Inconsistencies and over- or under-constrained sections of the mathematical system are detected and highlighted automatically.

Iterations of the initial engineering model can be made at any point of the process: Components can be exchanged or rearranged to compare scenario variations, and the objective of the computation can be reversed by turning output parameters into input parameters and vice versa.

The advantages of KBE technology also come to bear in product sizing: When the mathematical system is solved with a specific set of input values, constraints violations are detected and reported automatically. In addition to sizing by means of numerical solving, the software supports the optimization of products and systems as well as trade studies. The latter not only augment the interpretation and evaluation of the mathematical results and their implications for the design objective but also allow benchmarking them against any number of different scenarios.

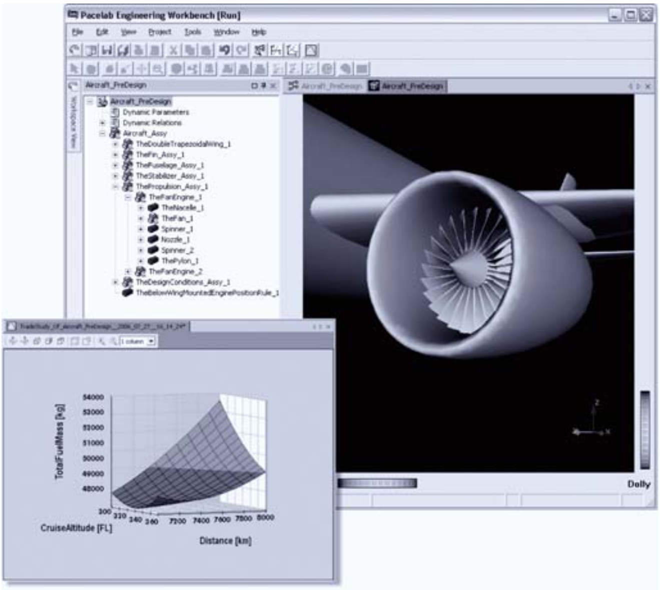

Fig. 6: 3D geometry and trade study carpet plot

The identification of optimum values for key design parameters is supported with a library of non-linear, constrained optimization algorithms, which can be supplemented with external optimization routines via a simple plug-in mechanism.

While the optimizer supplies a single optimum solution for each computation run, trade studies compute a whole set of parameter variations at once enabling more complex investigations of how variables in the mathematical system influence one another. A range of 2D and 3D representations of the investigated parameter variations supports the designer in finding the optimum trade-off. Trade studies can also benefit optimization investigations by providing an efficient means to assess the consequences of an optimum not being exactly met.

6 Conclusions

It has been argued that the quality and innovative strength of engineering design largely depends on giving design teams full access to corporate knowledge as well as the freedom to creatively explore a wide range of prospective options in the early phases of the product development process.

The implemented solution shows that an integrated software environment tailored to the specific requirements of conceptual and preliminary design can significantly contribute to realizing this potential. The design process is not only streamlined by supporting and automating routine activities at the level of the individual engineering task; moreover, the integrated environment actively encourages a multidisciplinary way of working and the long-term preservation and dissemination of corporate knowledge.

The resulting increase in efficiency and productivity and the reduction of cost and time to market helps to ensure not only the competitiveness of individual companies but also the progress in industrial design at large.

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A Way to Manage Calculation Engineers' Knowledge

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Abstract
Facing the industrialisation of computational mechanics domain, knowledge management can be a way to improve the efficiency and the reliability of results provided by calculations offices.
The present work is based on the assumption that intensive collaboration between engineers will support knowledge sharing, thus increasing the efficiency of the calculation projects. Our concern is to propose some simple and pragmatic ways to foster this collaboration and to build collective knowledge within calculation provider.
We present in this paper a part of the framework we developed to collect engineers' knowledge during calculation projects. This pragmatic collection method consists in associating object handled during a calculation project with context descriptors. This collection framework has been integrated in a knowledge management tool called KALIS[1].

Keywords
Knowledge collection, calculation engineer, FEA, knowledge management

1 Introduction

Nowadays, computational mechanics is becoming more and more an essential activity in product design. However, due to the specificity and complexity of the calculation activity, current industrial trends tend to externalise it, either by developing specialized and centralized in-house services, or by subcontracting with external calculation offices. In this domain, collabora-

[1] Knowledge about Activities as a Link to Information Sharing

tion remains mainly established on customer-supplier relationships. Such calculation offices have to manage projects of different sizes, involving customers from many different industrial sectors and with a large variety of problems. When companies have to achieve projects with many customers, they also have to manage particular knowledge about products, skills and practices of each customer.

Because of dead lines pressure and quality requirements of their customers, it has become crucial for calculation providers that engineers could be able to reuse knowledge created by others. Knowledge management approaches can leverage such issues by ensuring knowledge reuse and sharing through several projects and between calculation engineers.

In the computational mechanics domain, two knowledge management approaches try to overcome knowledge volatility and knowledge sharing issues in calculation projects. The first one is focused on KBE[2] systems that perform some tasks automatically [13], or process specific calculations [16]. Others provide technical support in selecting some analysis parameters for the calculation [10, 12] for example. The main drawbacks of such methods are the specificity of the issues they address, and the high development investments they need. Moreover, such methods are confronted with some social barriers, as they oblige the users to conform to a stereotyped model and they could be afraid of loosing their job, or being deskilled [7].

The second approach seems to be better suited to manage knowledge among various classes of technical problems. The aim of this second class of approach is to provide engineers with project and profession memories. Complete models [11], samples parts of studies [14, 15] or complete processes [0] are thus formalized (structured in a particular way, documented, validated, etc.) in order to be reused in future projects, or by other engineers. But, feedback on experience with these approaches reveals some limits. For example, crucial knowledge identification and formalisation remain difficult when actors are in project phase. Studies also highlight some difficulties encountered by the experts in creating detailed procedures about their working methods to make them public [9]. Moreover, in this context of heterogeneous studies and customers, it is difficult to allocate means to develop generic procedures, methods or models that could be reused in several projects, especially when their usefulness remains uncertain.

Facing to these knowledge formalisation and sharing issues, we made the assumption that intensive collaboration between engineers will support knowledge sharing, thus increasing the efficiency of the calculation projects. Our concern is to propose some simple and pragmatic tools to foster this col-

2 Knowledge Based Engineering

laboration and to build collective knowledge within calculation office. Such knowledge management tools have to be embedded in engineers' activities.

This paper presents the results of a field study in the form of participative observation undertaken within the design office of a calculation provider. We identified that some kinds of technical objects (information) are recurrently handled by experts during projects. Starting from the hypothesis that remembering the trajectory of a technical object's use could help others engineers reuse it [2], we propose a generic framework to associate information handled with the context of activity of calculation engineers. Finally, a prototype of software to associate these technical objects with their use context is presented.

2 An Investigation of Calculation Activities

Within a calculation office, engineers are often implied in different projects. Engineer's activities rely on Computer Aided Engineering (CAE) software and mainly consist in simulating and analysing the physical behaviour of mechanical devices under a particular focus. Deliverables are presented in the form of documents synthesizing relevant results and concluding on the product's behaviour regarding the customer's requirements. Therefore, engineers have to manipulate heterogeneous kinds of information like scientific books, technical documents, macros... In others words, they handle general knowledge about the modelisation of physical problems (linear, non linear, thermal …), about technological features (welded assembly, bolted joins…), or about customer product specificities (hydraulic gates, cable car,…).

Observation of engineers during several projects led to conclude that they share some knowledge objects and/or reuse them in other projects.

2.1 Which Data Support the Knowledge of Calculation Engineers ?

During a calculation project, engineers handle two kinds of information, characterized by their finality, their evolution and their management methods. Those kinds of information are also different if we consider them under a knowledge management focus.

The first ones are specific to the project and could be defined as project data. They consist in deliverables or input data (CAD models, planning, product data...) sometimes provided by the customer or developed by the calculation office. For example, calculation models and reports reveal project specific knowledge about the mechanical model that represent the product's behaviour and provide answer to the objective of the simulation. However, they do not formalize methodological knowledge about the calculation process of the engineer. The evolution of such information depends on project evolution (dead-lines, customer requests …). Thanks to the company's quality management system, such project data are often well managed by engineering and design departments (PDM…).

The second type of information is resource for the accomplishment of project activities. Such information is useful for an engineer during its calculation process, for example, an engineer can use a calculation worksheet to post-process the results of a FEA calculation or he can state calculation hypothesis regarding the mechanical properties of a material with a standard. Therefore, the use of such objects like calculation worksheet or standard, would point up some elements of the engineer's knowledge and know-how. We defined those objects as *Support Data* because they support an engineer in carrying out the activities related to his job.

This category of data concerns scientific standards or studies, calculation worksheets, Web sites, procedures etc… For the field of computational mechanics, some kinds of Support Data were described in [0]. Support Data are less project-specific than project data, thus, they can be reused or adapted in other contexts. Consequently, the evolution of Support Data in terms of specificity and reliability depends on the context of study in which they were used. We pointed up during our field studies that Support Data are used punctually during a project, and that they were not included in deliverables.

Although, calculation job experience is built upon a broad base of projects, in which Support Data strongly contribute to increase activity efficiency, we observed that only few Support Data are shared between projects because few common policies and specific tools exist to manage them. In fact, such information remains either filed in engineers' personal hard disk or sometimes in project archives.

We observed in industrial context that Support Data represent a strong opportunity for sharing knowledge between engineers by discussing about these boundary objects concerning particular engineering problems.

In calculation offices, it is possible to manage such Support Data by defining a common storage procedure and by describing them with metadata. However, this approach is still difficult for engineers when they are working on a project as it is time-consuming and often without any short-time benefit. Therefore, the knowledge collection process has to be as light as possible in order to be integrated in day to day activities. Associating metadata to Support Data could help in identifying their content; nevertheless, their use context might be lost. A way to overcome such barriers is to propose a pragmatic approach that enables to collect use context descriptors and associating them with Support Data during the project accomplishment.

2.2 A Way of Characterizing Calculation Projects' Context

Many studies in the CSCW[3] domain concern context modelisation to improve mutual understanding and collaboration in virtual teams [0]. Studies relate to context modelisation in a knowledge management approach [0, 0]. Organization, person, activity and physical circumstances are generally presented as main context categories. In our approach, context of activity relate to action framework and formalize actor's declarative knowledge.

Each calculation project can be broken up into independent studies, implying reduced size teams since a single engineer generally carries out a study. Consequently, context of activity could be characterised by project and study descriptors to define the general framework of the action:

- The name of the project in progress and the customer specifying context of the project.
- The scientific field and executive engineer's name characterizing context of the study.

Context of activity could be comprehensively specified by identifying action particularities. While indicating his current activity, the user formalizes some declarative knowledge. Describing the objective of action could support the formalization of engineer's motivations or even procedural knowledge (if he describes his process). Current activity and engineer's objective will be detailed for computational mechanics.

The observation of the calculation process at the activity level has permitted us to identify three main phases in which different activities are successively achieved. The following activities characterize the context of activity during a calculation process:

- The problem definition phase consists in understanding the problem and formulating assumptions that lead to define a physical model. Mains activities are:
  - preliminary analysis,
  - assumptions formulation,
  - criteria specification,
  - materials characterization.

[3] Computer Supported Cooperative Work

- The problem-solving phase relates to effective study accomplishment. Various tools may be used to build the simulation model. Related activities are:
  - modelling,
  - boundary conditions specification,
  - loads definition,
  - calculation processing.
- The results interpretation phase provides a conclusion on the product's behaviour, by putting in relation the obtained results with the study's initial objective, criteria and assumptions. Main activities are:
  - results post processing,
  - checking and controlling,
  - answering to customer.

During these activities, many kinds of Support Data are used. A framework to collect engineer's knowledge during a project is presented in the next section.

3 Drawing a Link between Support Data and Engineers' Activities

Figure 1 resumes the points discussed in the last part. In the context of a calculation project a study treats project specific data (input data to provide deliverables…). Some Support Data are required to carry out an activity. By associating Support Data with some simple context descriptors (project, study and activity descriptors), some declarative, procedural and motivational knowledge is formalized in relation to action. Real time tracking of those descriptors in a tool could provide a solution to our knowledge management issues.

A software prototype named KALIS has been developed during this study. The KALIS tool prototype is a common storage tool that aims at fostering information exchange within a profession team. Such shared information should be based on Support Data and activities described previously. KALIS establishes a link between users' activities and the information they use during a project. It does not aim at formalizing Support Data items' content but rather at assisting engineers in characterizing the context related to their activities.

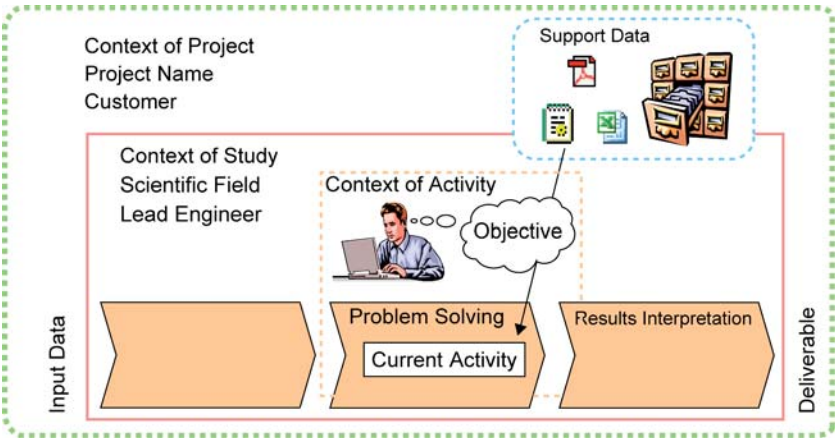

Fig. 1: Context, Activities and Support Data

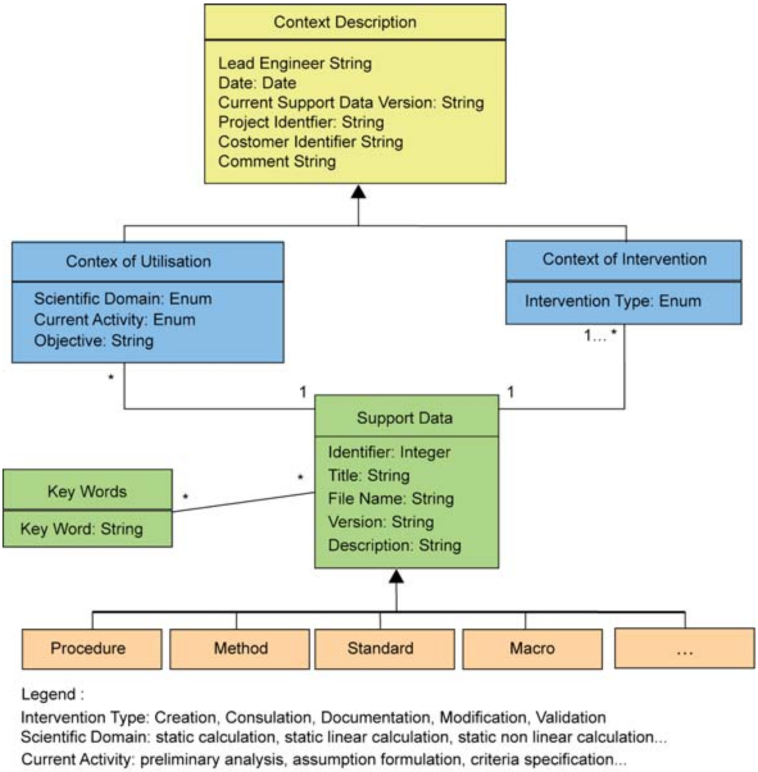

Fig. 2: Association between Support Data and context of activity

Figure 2 presents the framework of the KALIS tool. This diagram presents different kinds of Support Data that can be managed with KALIS. A Support Data can be described by specifying a title, and giving a free text description. Some key words can also be associated with Support Data.

Context descriptors are memorised when a user handle a Support Data. The generic class *ContextsDescriptors* describe the generic part of the context of a calculation project. Such generic contexts descriptors can be recorded automatically when the user log in the tool.

The class *ContextsOfIntervention* memorises project's context when a user creates, consults, documents, modifies or validates a Support Data. Each interaction with a Support Data is recorded, and a history list of interventions is created. For example, users can document or modify a Support Data to enrich its description. The documentation principle is based on wiki[4]-like self-regulating principle. The class *ContextsOfUtilisation* has been developed to memorise the use of Support Data during a project. The purpose of this class is to associate Support Data with engineer's activity descriptors, in order to make it possible to identify relevant resources and engineers' know-how for a particular task. Consequently, this class collects context descriptors at the project, study and activity levels as it was described in Figure 1. For example, when an engineer uses a calculation worksheet, project context descriptors can be stored automatically and he just has to specify the scientific domain, under concern, the current activity, and to describe the objective of the task. By specifying such contexts descriptors he associates with a Support Data some elements of declarative knowledge.

4 Conclusions

We presented in this paper, the framework of a tool called KALIS to collect some kinds of information handled by engineers during a project. This information, which is not specific to a project, is called Support Data. In addition, some descriptors of the past usage context of the support data make it possible to identify some ways of using it, and some experts of the domain within the company.

This light process of collecting engineers knowledge can overcome some of the issues faced in knowledge management. However, it is not enough to ensure knowledge sharing in an efficient manner, as a consequence, concepts will be developed in KALIS to foster collaboration between engineers.

[4] http://www.wiki.org

KALIS is being deployed within the calculation office of our industrial partner and we plan to get soon some experience feedback from this industrial implementation of such light knowledge collection approach.

5 Acknowledgments

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On the Way to Knowledge Awareness in Early Design

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Abstract

This paper discusses views on decision support in product development to identify factors of relevance when designing computer-based decision support for total offers. Providing services in form of physical artefacts offered as ‘functions per unit’ is at the heart of total offers. Total offers gain access to possibilities to ‘design in’ value added characteristics into the physical artefact, e.g., maintenance, monitoring, training, remanufacture. Contemporary computer tools seem to be insufficient to support a GO/NO GO decision for total offers. Relevant factors to take into consideration are to support learning and provide the decision makers with insights in a number of plausible ‘what-if’ scenarios to improve the solution space.

Keywords

Product development, decision-making process, decision support, collaborative engineering

1 Introduction

Globalization, increased competition, dynamic and constantly changing business demands are no exception for manufacturing companies in the Swedish industry. In this scenery, the companies have to manage aspects that could be considered as not compatible. For example, customers’ want individualized products at the same time as industry has to strive for standardization, since cost and time savings are paramount to be viable. The competition is not only about providing high-quality artefacts, but also to provide added value, i.e., a shift towards providing services.

The vision to differentiate physical products by supplying them as services are captured within the idea to provide customers with total offers [1]. The physical artefact, services related to that artefact and company specific knowledge are thought of as elements in the total offer. The total offer is in itself a service, since what is provided is offered as 'functions per unit'. Inherent in a total offer is the intention to provide customers with functions in time and place 'as-needed' in a long term commitment. The sale of functions also gain access to possibilities to upgrade and remanufacture the physical product, as well as provide for 'embedded' maintenance.

However, services are developed differently than physical artefacts. One difference is, *"Whereas goods are manufactured, services are performed"* [2] (p.65). The customer is present and contributes to the service development process. From a service perspective, the physical artefact is *"…just one element in the total, ongoing service offering. For a manufacturer, the physical good is a core element of the service offering, of course, because it is a prerequisite for a successful offering"* [3] (p. 9).

Archetypically, the view on products as physical things is embodied in a product development perspective [e.g., 4-6]. Yet, the intentions to provide a total offer affects this view by increased intangibility, for example, in terms of the final result, i.e., functions meeting the customers needs, and in terms of the development process, i.e., to design those functions into physical artefacts. The total offer calls for integrating a diversity of knowledge areas, e.g., business, design and manufacturing, accordingly affecting the product development process in the same way. Besides insisting on coordination and communication in a cross-boundary setting, making the right decisions at the right time is vital in this setting. Contemporary product development is extensively computer aided and the use of Computer Aided Engineering (CAE) tools is established in the industrial context. For example, finite element analysis techniques, as well as knowledge-based systems are used in design activities and, by tradition, bound to geometry modelling. Current tools, focused on hardware parameters, seem to be insufficient to support GO/NO GO decisions for total offers, since they do not provide an overview of a wider set of parameters. It is not apparent which aspects a tool to aid decisions in early design phases of physical artefacts sold in total offers needs to support.

Thus, the purpose in this paper is to describe views on decisions in product development to identify relevant factors to consider when designing computer-based decision support for total offers.

2 Data Generation

In general, data for the study presented in this paper has been generated during informal and formal meetings with companies affiliated to a research centre. Data for a functional product development process and a collaborative engineering model have evolved during these meetings. Specifically, data has been generated in a series of workshops, whereas two are in focus for this paper. The participating companies are found within manufacturing industry. There were 15 participants (10 from industry and 5 from academia) in one of the two workshops. 5 companies were represented in that workshop. The intention to focus on computer-based support for total offers evolved during this workshop, as well as the purpose for this study. Notes have been taken during the workshop.

In addition, the second workshop was performed as a 'future workshop' [7], at one of the affiliated companies. The workshop consisted of 8 participants from industry and 4 from academia. The group in a future workshop should include people who will get in direct contact with the tool that is going to be developed. Accordingly, the industry was represented by people from service, business, design and manufacturing departments. The academia was represented by people with different research interests. This made it possible to generate rich data. This workshop has been tape recorded. A future workshop runs in three phases, critique, fantasy and implementation phase. All were performed during the workshop. The critique phase highlights specific problems about the practice 'as-is', and is in focus for this paper.

3 Approaches to Decision-Making

Three approaches to decision-making are put forward by Mintzberg and Westley [8]. Firstly, the 'thinking first' supports planning and works best in, e.g., an established production process, since it is characterised by: a clear issue, reliable data, a structured context, thoughts that can be pinned down and control can be applied. This describes a rational decision-making process, where the steps are; (1) define the problem, (2) diagnose its causes, (3) design possible solutions, and (4) decide which is best and implement the choice. Despite being a frequent description, this is an uncommon approach and insufficient to explain decision-making [8].

Secondly, the 'seeing first' supports visioning and works best in, e.g., new product development, when: the combinations of many elements into creative solutions are needed, a key to those solutions is commitment and cross-boundary communication is vital. This approach suggests that actions might be driven as much by insights (seeing into) as by what is thought. Experiences and knowledge developed over years is a vital starting position. The seeing first is a base for the following incubation time, *"…during which the unconscious mind mulls over the issue*. [Then]…*there is that flash of illumination"* [8] (p.90). This *'eureka moment'* often comes when the rational thinking is turned off, e.g. in sleep. So, the actual decision of the choice to go for is more erupting than emerging. However, the verification, e.g., reasoning it all out for elaboration and proof and/or to write it down, takes time [8].

Thirdly, the 'doing first' supports learning and works best when, e.g., companies face disruptive technology. This situation is: novel and confusing, hampered by complicated specification and moved forward by a few simple relationship rules. When it is not possible to see it or think it up, a doing approach is supportive and encourages learning by doing [8].

A traditional approach to decision-making leads actors to view the situation in a binary way, assuming that the world is either certain or uncertain [9]. The former view makes the actors believe that the future situation is possible to predict precisely, and the latter view makes them consider the future as completely unpredictable. Actors that experiences very uncertain environments might not trust their gut-feelings and thus, suffer from decision paralysis. They focus on reengineering, quality management or internal cost-reduction programs instead [9]. To make sound strategic decisions when facing uncertainty, a binary view has to be avoided. The identification of a range of potential outcomes or even a discrete set of scenarios is a simple insight that is extremely powerful to determine which strategy is best [9]. A decisions-making process is intertwined in human analysis processes, thus a work-oriented approach to computational support seems promising [10].

4 Total Offer Readiness Level – the Idea

"*We have something to take into account which we cannot really do today"* and an increased intangibility in design decisions were emphasised in the workshops. The discussions rendered up in a need for understanding the maturity level on knowledge to provide total offers. Computational support was recognized as important to engineering activities and an interest for a computer tool to visualise knowledge maturity level emerged. The base for decisions was recognized to support GO/NO GO decisions for total offers.

The idea for a computer tool, to give insights in the maturity level of knowledge in the company as a whole and to give overview to the possibilities to provide total offers, was named Total Offer Readiness Level (TORL). The discussion was inspired by the technology readiness level used by NASA [11]. The technology readiness level is visualised by a 'thermometer' showing 9 readiness levels, where level 9 correspond to 'flight proven' system, see Figure 1. The overview given by the 'thermometer' was particularly appealing. Though, it was also recognised, by the participants in the workshop, that a total offer aim to encompass more than technical aspects and this is complicating product development, as well as the base for decisions.

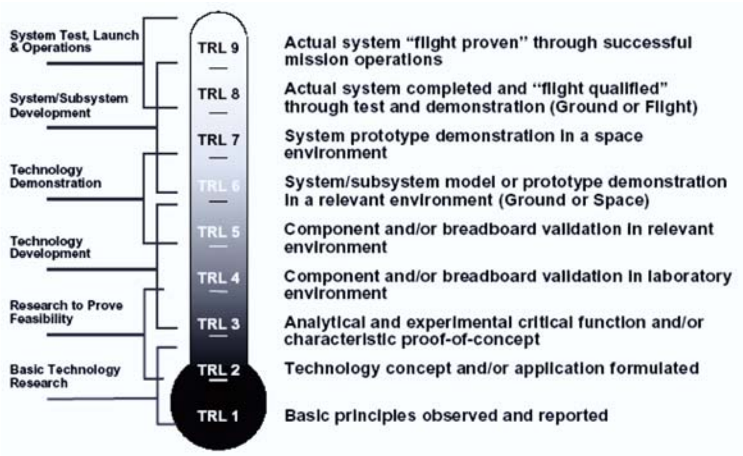

Fig. 1: NASA Technology Readiness Level [11].

Problems in Decision-Making Process – as-is

The informants talked about gathering people with relevant competences and people possessing the ability to influence the decision at higher organisational levels as critical to the decision-making process. It was emphasised that including high level persons in the meetings was necessary to give the decision-making process validity and stability over time. The informants could not describe how they know who had relevant competences, but they mentioned time as a constraint to gather the right people. *"A meeting the same day would not be possible since there would probably be a drop off of 90 %"*, they said. Two weeks notice was perceived as a necessary time limit to gather most of the relevant people.

Collecting facts from existing computer support were mentioned as easy to access. Existing support were, for example, management tools for project costs and time or process management tools. Tools for process management were described as relating to roles and not to positions in the organisation. *"How do I know who to talk with when problem occurs in the process?"*, said one respondent. The possibilities to predict costs for manufacturing over a longer time span was mentioned as causing problems. Many decisions were based on the fact of being an experienced team member, i.e., the task has been done in previous projects. However, the computer support for historical events was found sparse. Despite access to and possibilities to collect facts, the analysing activities were perceived as time consuming. The informants emphasised gut-feeling as important, and as a base for many decisions.

The design process was explained as a continuous dialog with customers about boundaries and possibilities for the physical artefact. The dialogue starts with some kind of document, for example a mechanical drawing or even a very simple form of drawing. From this starting position, the process was described as a long chain of analyses to perform. The procedure to acquire offers from subcontractors in the design phase was found particularly time consuming. One informant said *"Here we work very traditionally. To make an inquiry, via our purchase department, we have to have a drawing of some kind. The problem is that documents like that do not exist at this point. Purchase staff has to make guesses sometimes, or describe, as best they can, what they want."* He continued, *"And, you know, how you put forward your questions affect the answers"*, and emphasised that the level of details is important. Being focused on an overarching level, small details, e.g., a bolt, can be forgotten, even though utterly important.

The informants started to talk about decisions in the design phase, but realised that *"some homework had to be done before"*. This call attention to that *"the right decisions are made long before"* the design phase in product development starts.

5 Identifying Relevant Factors

The provision of total offers and the step towards designing physical artefacts to provide 'functions per unit' is likely to affect product development. These changes are in this context captured and addressed in a Functional Product Development (FPD) process. There are elements building up a total offer, e.g., training, maintenance and services, which by some of its characteristics could be perceived as based on experiences, i.e., tacit knowledge.

These elements can be handled as separate in product development, for example in aftermarket activities, however in FPD these aspects are thought of as having a holistic effect on the design of the product in early phases.

The design phases in FPD may need an extended design space to take, for example, life-cycle issues, into account. Early on it is needed to provide a number of business scenarios to be considered, e.g., to develop a physical artefact for transaction, or to develop a physical artefact for a total offer, or to adapt existing artefacts for a long term provision. Hence, it seems like FPD needs to handle ambiguity differently than traditional product development, e.g., to widen the design space and assimilate ill-structured goals into the design process. Activities in such a design process can be described as *"…creating visions and new ideas, formulating specifications on the basis of a range of competence, and mutual learning and understanding"* [12] (p.289).

Viewing product development as occurring on a line of sequences, downstream activities, e.g., product use, monitoring, maintenance and recycling, are needed to be understood as early as possible to influence design decisions. However, in this study it is identified that a design process seems to start earlier than what is thought of. At this stage information about the project are sparse, even tough resolutions has to be made. Initially, gathering people with relevant competences is necessary. The identification of these people is essential to give the decisions validity and stability over time. Furthermore, to enable integration and movement of downstream experiences into early phases, multifunctional design teams seem necessary. In this pre-design decision phase, it seems like computer-based tools needs to support identification of relevant resources and give an overview of when and how they can be used for the upcoming project. A supportive tool might also highlight what resources are lacking, as well as provide aid to identify key people in the organisation when problem occurs in the process. A tool for an overview of the maturity knowledge level should facilitate documentation of these problems to enable new knowledge to emerge based on these experiences.

The novel issues to take into account can be derived from the shift in view and/or from the need to integrate business, design and manufacturing knowledge areas. This integration is fundamental, yet not trivial. The respondents in this study has emphasised that gut-feeling serves as a base for many decisions. In our interpretation this is particularly happening in a pre-design phase when ambiguity about the contents in the project as such is prevalent. So, firstly, the nature of knowledge to integrate from some areas can be understood as tacit, thus not easily identified, captured, justified and formalised into computer applications. Knowledge can also be thought of as in constant change and evolving over time. The task to keep the database up to date might be overwhelming. As a result, there might become a gap between the knowledge maturity level held by people and the knowledge maturity level shown by the computer-based support tool. Thus, a situation where people do not trust the result given by the tool can occur. In light of this, learning capabilities could be a relevant factor to the design of the decision tool.

Secondly, people from divergent disciplines have different preferences for how to interact with a computer-based decision tool. This affects the visualisation of the result and the interface. The type of decision tool discussed here is aiming to give an overview of the company's knowledge maturity level. This understanding has to be provided on the right level and in the way that is comprehensible for those working and making decisions on that level. For instance, people from manufacturing functions are more interested in technical details than sales people. Salesmen would like to combine elements into an offer and be able to communicate with customers. In turn, early input from this customer communication is crucial to designers, especially if the offer include new product development. Besides being easy to use and provide for substantial improvements in the design process, the decisions support tool should increase the confidence for those who are using it.

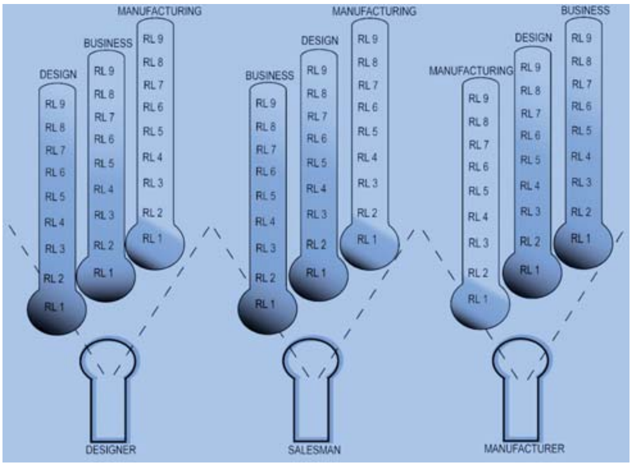

Fig. 2: Readiness Level views

Figure 2 is representing the idea, not an application view. The keyholes at the bottom of figure 2 symbolise a 'right' level view. Through these windows a set of related knowledge maturity level visualisations appear. These are in the figure presented as thermometers each showing nine readiness levels (RL 1-9); however in reality the visualisation might differ on different levels and from different views. It is important that the parameters represented are separate, not integrated into one and the same 'thermometer', since it is the relations between these that are of interest and provide an overview. For example, in figure 2, in the middle, the salesman can see that the business readiness level is high. This indicates, e.g., that agreement for total offers with customers is under discussion, the company strategy and vision are in line with total offer businesses and customer needs and/or requirements are identified. From this view, it can also be seen that the readiness level for manufacturing is very low. This indicates, e.g., that the company might not have appropriate production equipment, that manufacturing procedures does not exist and has to be developed. And, it can also be seen, that the design readiness level has not yet reached a predefined level. The decision to go for a total offer in this case is not recommendable, since it will not be possible to provide the functions needed by the customer. However, based on this overview, resources to increase the readiness level for design and manufacturing can be put in.

The shift towards service provision could be interpreted as new product development, i.e., the product offered to customers has changed by its nature from primarily a tangible artefact to an intangible service. A 'seeing first' approach [8] enables new ways of thinking and could be aided by a computer-based decision tool which allows visualisation of a number of 'what-if' scenarios and/or a range of potential outcomes. In this way a binary view on the situation as either certain or uncertain [9] can be avoided. A decision tool which provide simulation opportunities support a virtual 'doing first' approach [8], and in turn also provide learning possibilities without causing costly prototyping etc. The use of computer tools can provide swift access to information, yet the analysis of the result is human based.

6 Conclusion

The aim in this paper was to discuss views on decisions in product development to identify relevant factors to consider when designing computer-based decision support for total offers. The incitement for the study stem from a need identified in manufacturing industry to understand the knowledge maturity level in the company to be able to provide total offers to customers.

Additional knowledge aspects to take into account in total offers can be understood as tacit, i.e., based on experiences and interpretations. This kind of knowledge is difficult to translate into computer applications, yet it is identified as a relevant factor. Another relevant factor that has been identified is the importance to provide insights in the relations between each parameter, thus integration of parameters into one readiness level should be avoided. Decisions for novel and unfamiliar situations could be supported by visualisation and simulation of plausible outcomes and a 'learning by doing' approach. So, to support a GO/NO GO decision for total offers a computer-based decision tool seems to insist on taking learning capabilities as another relevant factor.

In this paper an engineering perspective has been prevalent. We have not considered a business perspective on computer tools to support total offers, still this is of most concern to improve decisions. Studies to further improve the understanding of parameters crucial to total offer readiness level is an ongoing work. For example, a demonstrator capturing some main ideas will be presented and evaluated in a workshop.

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Enhanced B-Rep Graph-based Feature Sequences Recognition using Manufacturing Constraints

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Abstract

In this paper we propose and investigate the possibilities offered by a new approach to find milling sequences and chains to optimize the machining time. Optimized milling sequences helps the process planner in understanding and setting the optimal strategy to reduce the part's machining time. Most previous chaining approaches concerned 2.5D pocket recognition for automotive mechanical parts. We present a new approach adapted to complex parts with a multitude of 5-axes orientation, focusing on our restrictive chaining algorithm based on the previously extracted machining directions. In a latter phase, the output sequences are filtered whereas we account the manufacturing fixture and machine-tool constraints.

Keywords

Face sequencing, Chaining, Manufacturing fixture, Machining directions, Machining feature recognition

1 Introduction

Research conducted in the field of Computer Aided Process Planning software studied the recognition of manufacturing features which included inherently their chaining strategy. Then, the system studied how to sequence the milling of these machining features. Within our approach, developed in the scope of the USIQUICK Project [9], we treated the problem in a completely different manner. Instead of translating the part into a set of machining features and pursuing with the process plan, we go to the lowest level of the part geometry, enrich it with information and propose a chaining strategy to deduce the manufacturing sequence. For more information, please refer to [1, 2, 4, 11].

Within the scope of our article, we try to propose an approach to find milling sequences based on a restrictive chaining algorithm split into two main sections. The first would generate the Chaining Graph (CG). The second section is applied to “restrict” the chaining graph to machinable solutions. This restriction is made by including manufacturing fixture constraints and checking the proposed chaining falls in the machine rotational capabilities.

2 State of the Art

Three generic major steps can be highlighted in the literature survey on generative CAPP systems: (1) Feature recognition, (2) Operation planning and (3) Set-up planning. The former consists in identifying machining features on a part from the solid 3D model, the second deals with matching a machining operation to a feature, while the last groups the process operations into set-ups and sequence operations within each set-up.

Considering feature recognition, most approaches rely on the attributes and topology of elementary geometric elements (edges, vertex, volume…) to recognize them, taking the assumption that a preferred direction of tool axis is known. Indeed, most of the mechanical parts to machine are 2.5D parts; therefore the tool axis is constant during the machining and is easily extractable from the overall shape [10]. Techniques for 5-axis features (which are not easy to classify, therefore more difficult to recognize) are still confidential and not clearly explained [6].

To conclude, most approaches mainly focus on geometrical aspects to set the final geometry of extracted features. Few authors consider some manufacturing constraints other than generic rules affecting geometry. Gaines et al. [3] propose an approach to construct complex features considering existing tool shapes (tailored made) in the workshop. Raman et al. [8] overcome the “predefined features” limitation taking into account tool and process capabilities while interpreting the design. Lee et al. [7] propose some alternative 2.5D feature set considering various tool axis orientation for prismatic parts.

The proposed approach is quite innovative because it relies on the extraction of elementary faces (such as planes or cylinders) and their machinability attributes (such as their milling mode) to identify the possibility to mill them in a chain sequences. It has been developed to identify flank milling chain sequences of planes encountered on aircraft structural parts, but is not limited to this family of parts. Techniques to extract machinability attributes from planar surfaces in a 5-axis context are detailed in [5].

3 The Restrictive Chaining Approach

In the following we present the main guidelines for the restrictive chaining approach. The mechanical parts we consider are five axis parts with particular requirements (figure 1).

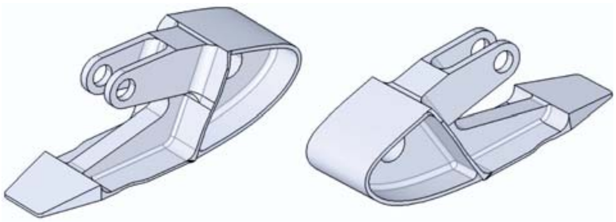

Fig. 1: Studied mechanical part

The general algorithm is essentially composed of two main phases: section 4 and section 5. The input would be a mechanical part. First, all the EMFs related to the current mechanical part are extracted. Once we obtain the EMFs, we study all the possible face sequences based on a 7 step sequential algorithm presented in section 4.

The last step would confirm the computed face sequences using the manufacturing constraints. A sequence is a continuous chain of faces that are potentially machinable along the same machining strategy. Machining direction sets construction, Accessibility checking step and Sub-sequence chains restriction constitutes the three different steps that outputs the final machining sequence. Different face sequences computed in the previous section might find themselves split unto two different sequences or might even be totally disqualified.

4 Face Sequence Extraction

This part of the general algorithm (section 4) aims to generate the total face sequences. The latter will be then reduced taking into account manufacturing constraints (section 5).

4.1 EMF Definition

EMFs, Elementary Machining Features, are nothing but the different faces of the CAD part completed with many technical attributes. These attributes enrich the face with some information, transforming it to a "smart face". This latter concept means a face that knows how to be machined. The different Machinability Analysis conducted along the many computed attributes, enable the face to search in its surrounding which other faces to machine in the same manufacturing fixture, which machining mode will be used, what are the potential manufacturing tools to be used.

As told before, an EMF integrates a lot of attributes. We shall now introduce 4 essential attributes that the face is enriched with (over 15 attributes):

- *Face type*: this basic attribute refers to the face geometrical type. An EMF can be a planar face, a cylindrical face, a conical face, ruled face. An EMF face type is declared unspecified when it is not one of the previous face types.
- *Fillet identification*: it allows knowing if the face is a junction face between two others that perform certain functionality, or if the face is a stand alone face.
- *Machinability factor*: the different faces are tested for end and flank milling, and the attribute is added to the face. Some planar surfaces are suitable for both milling modes, it is then up to the chain sequence to force a certain machinability factor
- *Machining directions*: the face different machining directions are the main input used in the second phase of our algorithm. Based on trade rules and common sense of process planners, an automation to extract the potential machining directions is applied on the part and stored within the EMF object.

Finally, an EMF is an attributed face. From all the EMFs, we generate an attributed face adjacency graph called a 'chaining graph', where each node of the graph is an EMF and each link is an edge connecting two EMFs.

4.2 Chaining Links

The chaining links splits the junction types between different faces. The differentiation is made through the sharpness of the common edge between two different parts. The sharpness is the term used to describe on how the transition is made. A link can be Open (O), Closed(C), Tangent Open (TO) and Tangent Closed (TC) [KYP 80].

The chaining links are split into 6 categories, and a color attribute is given to each. This split results from the study of the ‘interesting’ links that might indicate a certain chain. Figure 2 presents the different chaining links.

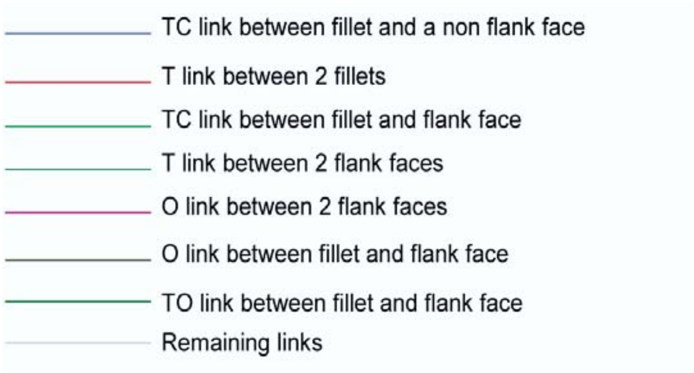

Fig. 2: Chaining link categories

Red links are a direct indication of the existence of chain sequences. We expect then from one side a flank milling chain and from the other a simultaneous end milling. Dark Green links forces a flank milling chain where the light green set the guidance.

4.3 Chaining Graph

The chaining links end up drawing the total part chaining graph with a clear forward proposition to the different sections that we’ll be realized. The chaining graph is a normal part chaining graph which explicit the surrounding of the face. The addition is simply the links are colored respecting the chaining links previously presented. The different faces are split depending of their machining mode. If a face is to be flank milled then the face will be identified as {F} + {id} where id represents a different number for each face. The letter {C} will be used to represent fillets and the letter {B} to represent planar surfaces that will be end milled.

4.4 Chaining Algorithm

The algorithm relies heavily on the ‘smart face’ ability to understand its surrounding and to say “these surrounding faces belong to the same chain sequence as I”. The algorithm is composed of the following steps:

1 **Fillet chains identification**
The first part is to split the fillet faces into 4 categories: Open fillets, Singular closed fillet, closed chain of closed fillets, and open chain of closed fillets. These 4 categories are identified through a dedicated algorithm.

2 **Pocket chains construction**
Based on the closed chain of closed fillets, pockets are identified. Usually closed fillet chains are linked to end milled faces from one side and three different types of ‘flank milled’ faces from the other side. The three different types can be regular pockets, open pockets and strip ones (figure 3 is cut in middle to show pocket natures).

3 **Open flank milling chains construction**
Based on the open chain of closed fillets, this set identifies regular flank milling chains where simultaneous machining is usually performed. Usually, these fillets are adjacent to an end milling EMF from the other side or series of end milling EMF in multiple depressions.

4 **Contouring chains construction**
The algorithm is based on the open fillets which junction in between free EMF. These open fillets often describe the contouring strategy to be used. It is to mention contouring chains recognition is not restrictedly based on open fillets.

5 **Flank milling ruled driven**
The remaining ruled surfaces still unaffected to any sequence can propagate the flank milling mode to their surrounding through the chaining links study (section 4.3). In Example a ruled surface linked through TC sharpness to a planar surface will create a flank milling sequence and so on.

6 **End milling chain**
Planar surfaces connected through tangent links are to be end milled together.

7 **Single closed fillet chain**
Single closed fillets are mainly combined with a close-by end milling and would not indicate any chain. However in the particular case of being next to a flank milled ruled surface it might be neglected.

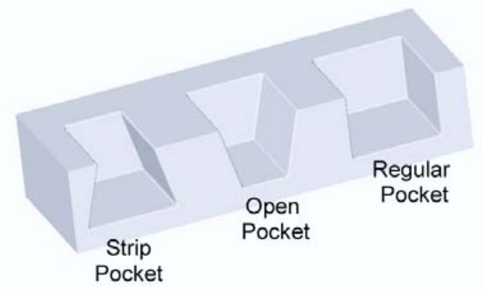

Fig. 3: Different pocket natures

By processing these steps, the majority of face chain sequences will be found. Tests were made on multiple parts and proved the proposed algorithm. Nevertheless it is not to forget that this chaining algorithm remains the approach of a machinability analysis, and the results are to be presented for the process planner to approve or to reject them. Sometimes, the same face belongs to two different sequences. That is often an indication that this face might be split and manufactured through two different chaining sequences.

4.5 Algorithm Execution

We propose to present how the algorithm proceeds in order to better explain the method to obtain the face chain sequences. We assume the EMF extraction is done. The figure 4(a) shows the different fillet categories: the red consists of the open chaining of closed fillets, the green of single closed fillets, red for open chain of closed fillets and orange for open fillets. Once step one of the algorithm is finished, we proceed to study the closed chain of closed fillets or the blue chain on figure 4(b). The chaining graph links the faces {F21, F22, F23, F24} all together. The junction fillets {C21, C22, C23, C24} are linked to {B21} from the other side which defines the global chaining. This pocket is similarly found from the other side of the part. Once we end up the closed chains we pass to step three and studying open chains. Figure 4(c) shows an open chain {C1, C2, C3, C4, C5, C6}. Due to space requirements, we won't show the next algorithm steps. However, the extraction process is the same.

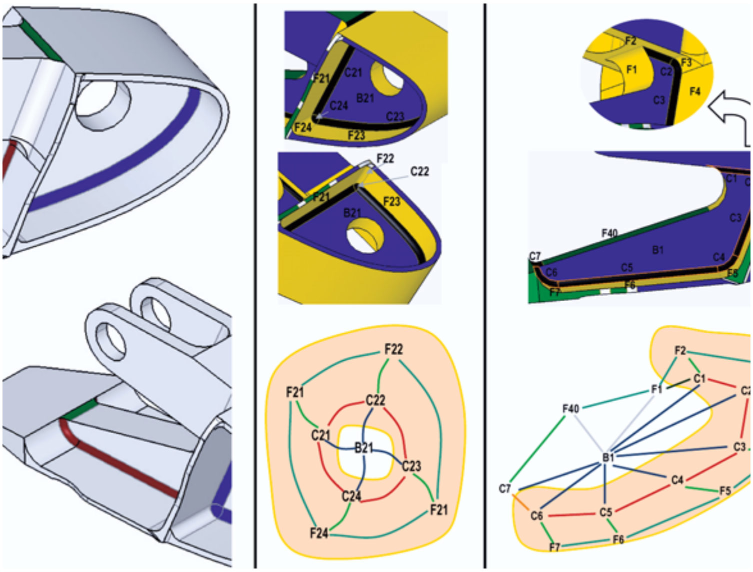

Fig. 4: Algorithm execution

5 Restrictions with Manufacturing Constraints

Feature recognition and machinability analysis are local analysis phases (feature-level), sometimes enhanced taking into account global constraints such as its surroundings topology (real visibility of the features considering the whole part volume; attributes of neighbor faces…). The results of these phases are alternatives elements, such as a combination {feature, operation}, that can be picked up to compose a process plan.

Set-up planning is the global analysis phase (part-level) that will combine these alternatives elements to generate a plan that is optimal considering a global objective function. The algorithm proposed take part within the machinability analysis: it is clustering elementary elements into chain sequences in order to ease the set-up planning activity reducing the number of elements to deal with. Although no decision relative to the generation of the plan itself has to be made, the feasibility of these chains (considering available information at the calculation time) have to be checked before displaying them to the planner. Given a machine-tool, the idea of this restriction is to propose the list of alternatives chaining sequences that are possible as long as the set-up orientation has not been defined.

5.1 Manufacturing Fixture Constraints

The global constraints considered in this paper are due to the limitation of the rotational axis of a machine-tool. In the configuration of figure 5, the joint design of the axis A limit its rotation from 0° to 20°. The parts are mounted on a cube, which limits the rotation around B axis from -90° to 90°.

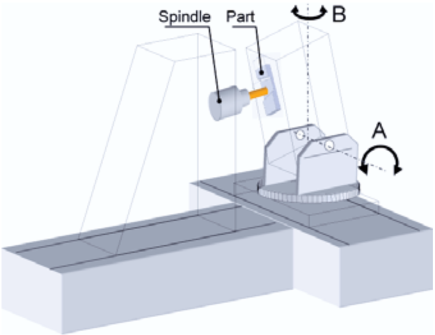

Fig. 5: Rotational Constraints

Considering the generalized pocket shown on figure 6, the difference of angles between opposite walls (30° and 25° in the perpendicular direction) overcome the possibility of rotation of the spindle about axis A. Therefore, the pocket chain construction will compute a flank-milling operation chaining the 4 flanks of the pocket but this operation will not be achievable on the considered machine-tool.

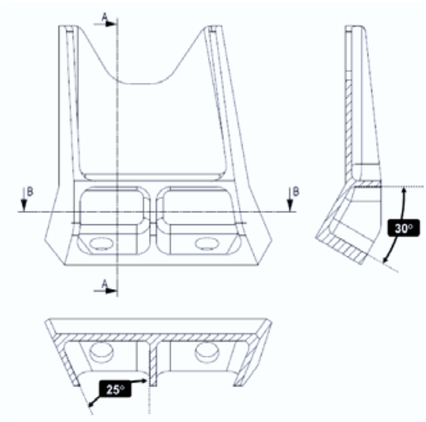

Fig. 6: Generalized Pocket

The main idea is to add an extra step to the algorithm of section 4 in order to restrict the theoretical chaining considering some constraints that are already known when starting the process plan, such as the machine-tool configuration. The objective of this extra step is to split the theoretical sequences considering the angles between the various flank-milling directions that are needed in the sequence.

5.2 Algorithm

The algorithm relies on an existing visibility based algorithm developed by Kang et al. [Kang 97]. A simplified version of this algorithm will be considered as a black box, taking a set of machining directions as in input in order to compute the minimum "spherical rectangle" as an output (fig. 7). The minimum spherical rectangle, defined by the two parameters, is a visibility-based model that represents the minimum rotations needed on A and B axis for the spindle to reach the considered machining directions.

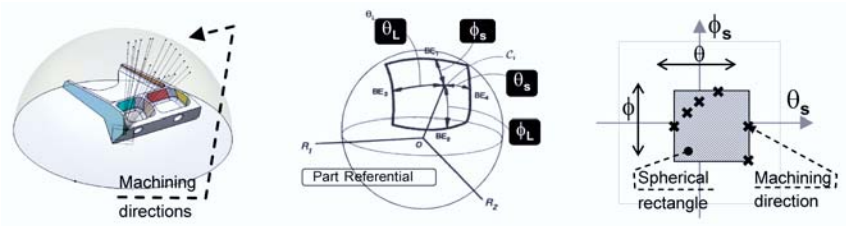

Fig. 7: Kang's algorithm

The spherical rectangle fits in the machine-tool rotational axis ranges if max[α, β] < max [A,B] and if min[α, β] < min [A, B]. The proposed algorithm to restrict a chaining sequence CS = {F1, Fi,…, Fn} associated to a set of machining direction DCS={machining directions} is presented below:

0. Initialize i=1
1. Check the feasibility of the theoretical chain CS
Compute the minimum spherical rectangle
(Kang's algorithm) with DCS
Check if the spherical rectangle fits in the machine-tool
rotational axis ranges
→ If not *GOTO* 2 else CS is machinable
2. Define a subsequence CSi*
Select a face i till i=n / CSi* ={0}
3. Construct the Sub-Sequence of CSi*
j=i
The chain CSi* = CSi*+Fj
3A. Extract machining direction CSi*
Compute the minimum spherical rectangle of CSi*
Check if the spherical rectangle fits in the machine-tool
rotational axis ranges
Yes → *GOTO* 3A with j=j+1
No → Substract the face Fj from CSi*, store the machin-
able
sub-sequence CSi* .
GOTO 2 with i=i+1

6 Results

From an initial chaining sequence, the presented algorithm may split it into sub-sequences that are locally achievable on the given machine-tool. Some faces may be present in several sub-sequences. The selection of the right sub-sequence(s) between the computed set will be made during the set-up planning phase, considering global constraints from feature interactions, tolerances and fixture possibilities.

Depending on the wishes of the planner and the process planning strategy of the sector, the identification of the "larger" 5-axis chaining sequences could ease the set-up planning orientation or the decision about the number of required set-ups.

7 Conclusion

This article presented an inherent manner to compute the machining sequences. The result allows the process planner to imagine all the potential machining chains he can apply to realize the part. This effort done in a post design – pre process planning - phase provides essentially a certain understanding of the design which can reduce the time needed for the process plan generation and thus the total cost. This effort is being realized with Dassault Systemes Component Application Architecture CAA ® & CATIA ® V5's API.

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Facilitating Product Development with the Help of Knowledge Management: the McKnow Platform

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Abstract
Product designers and other professionals spend a large part of their time in search of previously gained information and knowledge within and outside company borders. When unable to find what they are looking for, these professionals often resort to reinvention of the wheel. This paper introduces the McKnow platform, a framework on which algorithms are developed that support a quantified approach to knowledge management. Key aspects of these algorithms are automation and user-orientation. Several offered functionalities are described, as well as conclusions from their experimental evaluation.

Keywords
Knowledge management, text mining, user profiling, clustering

1 Introduction

During the last few decades, the industrial world has witnessed a growing awareness of the importance of knowledge. Knowledge has been recognized as a dominant economic factor for innovation oriented enterprises. This is not at all surprising. The value of a company is only partly represented by its tangible assets, such as buildings, equipment and capital. The added value of a product is primarily determined by the knowledge and experience of the people that design and produce it. This knowledge is often tacitly ungraspable, residing in people's heads, but it can also be made explicit, for instance by writing it down in product specifications and manuals [7].

Many companies have taken on the challenge of managing this knowledge in the most effective way, often making use of supporting technologies, here referred to as knowledge management systems (KMS). A large variety of this type of systems is commercially available on the market today. A typical problem that arises when knowledge is not managed, is the inaccessibility of this knowledge to others and, as a result, the phenomenon of reinventing the wheel. Time studies indicate that, throughout a design process, designers spend on average 19% of their time - with peaks to 36% in early conceptual design phases – on information gathering activities [8] and [2]. An efficient KMS, that allows advanced searching in a company's existing knowledge base, could seriously reduce these percentages.

The unavailability of knowledge takes on dramatic proportions when product designers have to start from scratch, ignorant of research or development work that has been performed earlier by co-workers in the same company. Very often, especially in large enterprises, employees have no idea what other project groups or divisions are working on, let alone the exact details of the techniques or products they design. A survey by KPMG reports 63% of companies complaining about this reinventing of the wheel, as opposed to 45% of those that have implemented some kind of KMS [5].

This paper describes McKnow, a platform on which a collection of methods and algorithms for knowledge management has been developed.

The next section describes the structure of the platform. The third section describes functionalities offered by the platform and discusses some experimental results. The last section contains the conclusions of this paper.

2 The McKnow Platform

The McKnow platform was conceived in 2001 as part of a project conducted at the Centre for Industrial Management of the Katholieke Universiteit Leuven in Belgium, and has been the subject of continuous research since then. The project focused on automated and user-oriented methods and algorithms for knowledge management, with the explicit objective to support product developers and other professionals by reducing the time necessary to locate previously gained knowledge or information that is relevant to their current task. This paper discusses the platform and the functionalities it offers.

Automation and user-orientation are two important aspects of all algorithms that were developed as part of the platform. Extensive automation reduces the amount of time spent on maintaining the system, both by administrators and by the end-user. User-orientation, or personalization, takes into account the personal background of the end-user, allowing the knowledge management system to provide qualitatively better answers, tailored to a specific user.

2.1 Tacit versus Explicit Knowledge

The McKnow platform takes into account both explicit and tacit knowledge. Explicit knowledge can be found in documents into which a specific combination of data and information has been written down. Typical documents are research papers, product specifications, technical reports, progress reports summarized in presentation slides, etc. Of course, not all documents are equally dense in knowledge.

A larger portion of the knowledge base of a company is tacit however. It is ungraspable and mainly resides in the employee's head. It is, amongst others, based on training, experience and feeling. In order to include this type of knowledge in the system, McKnow provides user profiles that reflect the expertise of the user. These profiles are based on documents that have been written or read by this user, where written documents indicate expertise, and read documents reflect an interest. The profile does not contain knowledge itself, but it points to the person who does have the relevant expertise.

Most importantly, the use of documents, both for explicit and tacit knowledge representation, has the benefit that it comes without additional costs. The documents are written as part of the professional's daily tasks, and their inclusion into the knowledge base can happen automatically.

2.2 Structure

The basic structure of the McKnow platform is depicted in Fig. 1. The main input for the algorithms developed on this platform are documents, as described above. These documents reside on the company intranet, mainly on file servers. They are automatically retrieved, analyzed, and entered into the document pool on the left-hand side of the figure. This is done by a text mining process called indexing, the resulting document pool is dubbed "the index" [1].

The right-hand side of the figure shows a second pool, containing the users of the system, i.e. the employees. They are in search of knowledge concerning their current activities. As described in the previous subsection, the users are reflected through user profiles, which are based on documents written and consulted by the user.

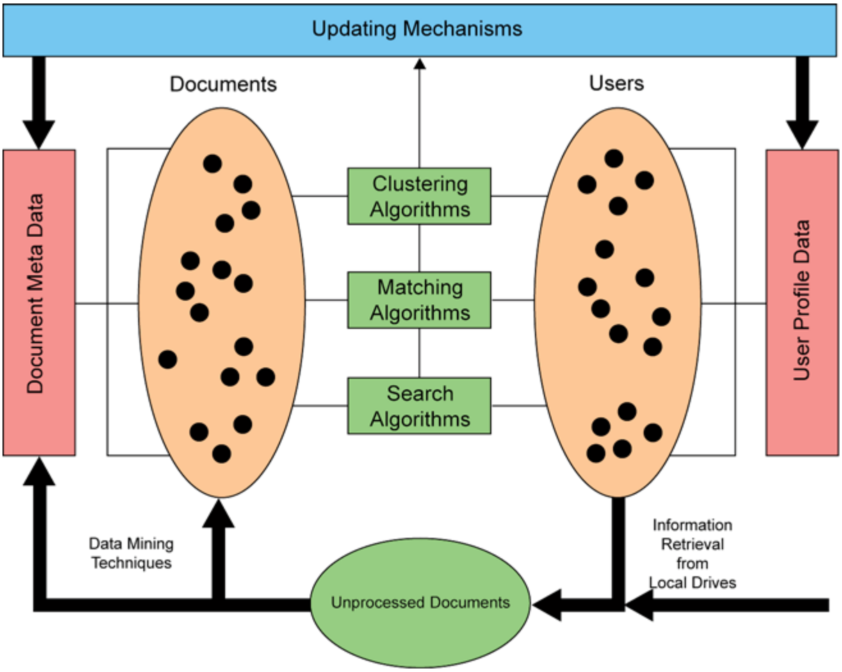

Fig. 1: The McKnow platform

Based on these two groups, documents and users, explicit and tacit knowledge, algorithms have been developed. These algorithms are categorized into clustering, matching and search algorithms. Clustering algorithms will discover similarities between different documents or users. Matching algorithms will link (clusters of) documents to (clusters of) users and vice versa. Search algorithms enable the user to locate both explicit and tacit knowledge inside the knowledge base.

On top of these components reside updating mechanisms, which adapt document and user profiles, depending on user interaction with the system as well as new documents or users entering the system.

2.3 Document and User Representation

The documents in the system are added to an index by converting them into vectors. Considering the scope of this paper, a full technical detail of this procedure is omitted. For a good understanding of the next section, it suffices to know that a document is transformed into a vector with

- Dimensions: all words in the vocabulary of the document corpus
- Weights: the importance of each word in the document, a weight of 0 being assigned to words that do not appear in the document under consideration

User profiles are constructed by making a linear combination of specific document vectors, and thus are vectors themselves, residing in the same space as the documents.

3 Functionalities

The algorithms developed on the McKnow platform can offer a wide range of functionalities, several of which will be discussed in this section. All functionalities are geared towards better and easier access to knowledge that is present in a company. This improved access will free up extra time for the professional to spend on his core tasks.

3.1 Knowledge Identification

A first functionality that is offered by the platform is knowledge identification. Its goal is to discover in which domains the company has expertise. This is mainly accomplished by clustering [4] the entire document corpus that can be found on the company's intranet. Clustering will identify groups of similar documents. The content of a document is represented in the index by a weighted vector, and the contents of a cluster can be summarized by making a linear combination of all document vectors involved. The result is a vector for each cluster composed of a series of words, ranked according to importance. Generally, these stems are descriptive enough for the professional user to discern the various topics that are covered in the dataset.

This procedure can be applied to an entire company, but also on a lower level, such as company divisions. Furthermore, it can be used to compare different divisions or companies to evaluate them for possible overlaps in expertise. This can be an indication of, for instance, redundancy within the company, or the need for a structural reorganization.

This functionality has been tested on several datasets, both from industry and the academic world. In general, the employed algorithms succeed in identifying key concepts that typify the knowledge contained in the dataset under consideration. An experiment with data from an engineering company, for instance, led to the conclusion that the identified knowledge was strongly correlated with the individual projects conducted at the company.

This could be confirmed by the company, because the data that was supplied as input to the algorithms, consisted of documents on various long term projects that had little overlap in technical content.

Another experiment was conducted using data from several research groups from three university departments. Some of these research groups, e.g. Physiology and Accounting, have little in common. Others, such as Artificial Intelligence and Management Informatics, work on similar topics. The employed algorithms succeeded in detecting the overlap in knowledge between different research groups, as well as distinguishing research groups that have no overlap.

3.2 Knowledge Localization

Knowledge localization is used to discover who has specific expertise within the company. The most important technique to provide this functionality is user profiling, which assigns an expertise profile to each individual employee. It is advisable to assign multiple vectors to employees with multiple expertise domains. If all documents that can be linked to one employee are used for one collective profile vector, this vector will contain words from multiple domains, competing for importance within the vector. As such, stronger domains can suppress others, giving an incomplete view of the user's competences.

The user profiles can be integrated in a search engine, because they are identical in structure to document vectors. This means that it is possible to find expertise within a company simply by launching queries through the search engine.

Secondly, the profile vectors of multiple employees can be clustered using a clustering algorithm [4]. This results in clusters of similar profile vectors, indicating which employees share expertise. Because user profiles contain multiple vectors, an employee can be situated in multiple clusters. These clusters can be used as a basis to construct communities of practice [9], an increasingly popular approach to encourage people to share knowledge. This can be demonstrated with the following small scale test case.

For this experiment, documents from the Reuters RCV1 dataset [6] were used. These are all press articles, categorized according to a predetermined classification scheme. Documents were selected from the topics in Table 1.

Tab. 1: Reuters dataset

GDEF (defense)	GSPO (sports)
GENT (arts, culture & entertainment)	GTOUR (travel & tourism)
GENV (environment & natural world)	GWEA (weather)
GFAS (fashion)	
GREL (religion)	
GSCI (science & technology)	

Out of these documents, a series of user profiles were constructed, as if representing the expertise of several journalists. No overlapping documents were used between users. The different topics were assigned to the users as shown in Table 2.

Tab. 2: Users with their respective expertise domains

User	**Expertise**	**User**	**Expertise**	**User**	**Expertise**
A	GDEF GFAS GREL	C	GSCI	E	GSCI GSPO
B	GENV GFAS GREL GSCI	D	GSPO GTOUR GWEA	F	GDEF GENT GWEA

As such, the dataset contains user profiles with 1 to 4 vectors, on a range of topics. Most of these topics represent an expertise that is shared by several users. The results of the experiment are summarized in Figure 2. The underlying dendrogram describes the relationships that are discovered between the profiles. The profiles are listed alongside the Y-axis. As the dendrogram advances along the X-axis, the profile vectors are clustered one by one. The calculated relationships between users are exactly in accordance with the relationships expected from the overview in Table 2. An additional discovered group is indicated by the darker grey rectangle. Although not expected when examining the original data, a relationship between "environment", "travel" and even "entertainment" is not far-fetched.

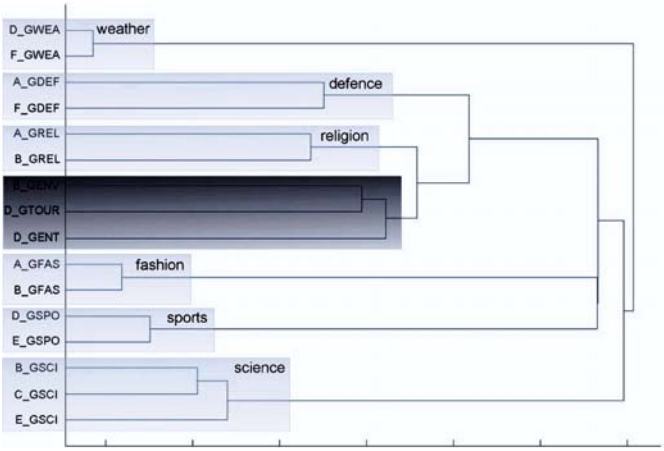

Fig. 2: Dendrogram of the clustering results

3.3 Search Functionalities

This section will describe several search functionalities that can be offered through the integration of the McKnow technology with a search engine.

Expertise Search

Because user profiles are combinations of documents, they can be searched for in the same way as a typical search engine does for documents. This allows for end-users to quickly find colleagues with a specific expertise. The profiles are constructed automatically, so there is no need for a "yellow pages" system that depends on employees keeping the entries on their expertise up-to-date.

Fuzzy Search

The objective of a fuzzy search functionality is to expand the results of a normal search with other relevant results that are not found by the normal search. An example of this is synonymy. A search for e.g. "bicycle" will yield other results than a search for "bike". Both have the same meaning, but are not interpreted as such by a computer. A query on "bicycle" will therefore not return documents containing the word "bike" unless, of course, it contains both.

The problem of synonymy can be addressed by reducing the amount of dimensions in the vector space that contains the document vectors. This can be achieved through Singular Value Decomposition of the original vector space and projecting it into a smaller space defined by k eigenvectors. The dimensions of this new space are called factors or concepts. These concepts are each a collection of dimensions from the original space, where dimensions that frequently occur in the same context are mapped together, including dimensions that represent synonyms [3].

By transforming a query to this new document-concept space, it is automatically expanded with similar stems from the same concept. The term "bike" will now automatically be added to a query on the term "bicycle", together with other relevant words, thus expanding the result list with other relevant documents.

Profiled Search

When two people use Google, they will both get the same results, even though they have a different background and interests. In the context of a company, a product designer querying on a product name has totally different interests than an accountant querying on that same product.

Profiled search takes into account the background of an employee using the search engine. This is done by combining the query terms with one of the employee's profile vectors. This combination can be weighted, allowing to assign a variable weight to both query terms and profile.

This combination between query and profile has two goals. On the one hand the profile filters out irrelevant documents from the result list. On the other hand it adds relevant documents to the result list by expanding the original query using the user profile.

Recently, an experiment on the effectiveness of several search functionalities was conducted by the authors at an international engineering company. Part of this experiment involved the enhanced document search described here. A group of 20 engineers participated in the experiment, several of them testing their profile in combination with document search. A total of 27 queries were performed with a profile in the background. The users were free to choose which profile to apply. After processing, two result lists were returned, one using the profile as background, the other without using the profile. The participants were then asked to rate the documents that were added to the result list when applying the profile, and those that were removed. They rated on a scale of 1 to 5 with 1 being "not relevant to my query" and 5 being "very relevant to my query". The documents that were added had a mean score of 3.29, those that were filtered out had a mean score of 1.44. This indicates that search results are improved when using the profile by increasing the precision of the selection procedure.

4 Conclusions

This paper introduces the McKnow platform, a framework on which algorithms are developed that support a quantified approach to knowledge management. Key aspects of these algorithms are automation and user-orientation. Several offered functionalities are described as well as their evaluation in both realistic and artificial environments. The algorithms are shown to perform well, thus supporting the desired functionalities.

Deployment of these functionalities in a product development environment would provide the professional end-user with a significant decrease in time wasted on searching for information and reinventing the wheel.

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Integration of Learning Aptitude into Technical Systems

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Abstract
The higher level of intelligence of multi-disciplinary systems results from the opportunities coming along with further developments within informatics. This opens up new opportunities to develop cognitive technical systems, which independently improve and optimize their own performance. However cognitive abilities in technical systems are always tied to their embodiment. The acting in terms of the system's intended purpose is based on data collected by the system from its environment or provided by the system itself. Furthermore it is necessary to integrate learning aptitudes in the technical system. The paper describes methods to include learnability for realizing cognitive abilities in a technical system.

Keywords
Mechatronics; cognition; learnability; product development

1 Introduction

Integrating cognitive abilities into technical systems can be regarded as a consequent further development in mechatronics. Generally, the cognitive abilities of the human being are considered to be the ones that enable it to behave intelligently and und flexible in most diverse situations. At the same time, each discipline dealing with cognition has its own expert-specific view of handling it. This eventually redounds to the fact that terms being associated with cognition such as “intelligence” and “learning” are used very variedly, therefore are diluted, and cannot necessarily be explicitly defined. Therefore to enable implementing cognitive abilities into technical systems, cognitions from non-technical fields of research such as cognition sciences and psychology need to be incorporated for the interpretation of such terms in the context of the designing of technical systems. Decisive thereby is that cognitive abilities cannot simply be reduced to a high-performance information processing system. Rather it is imperative also to incorporate the complete system in its structure into the considerations. Therefore, considerations on the embodiment of cognitive technical systems stand in the focus of this article.

2 Cognitive Technical Systems

The term cognition derives from the Latin term "*cognoscere*", which means as much as *percipience, recognition*. Modern cognition science subsumes under that term the properties of: percipience and recognition, encoding, memorizing and recalling, thinking, problem solving, the motor-functional control and the use of language. In order to acquire cognitive abilities, it is thus crucial that all those properties must be achieved. The degree of cognitive abilities is rather distinguished by the degree of development of those properties. For example, when a form of language is used for communication, as the human being does it, a very high cognitive degree is achieved. However, simpler types like communication via symbols or menus on the computer for instance can also absolutely contribute to cognitive properties.

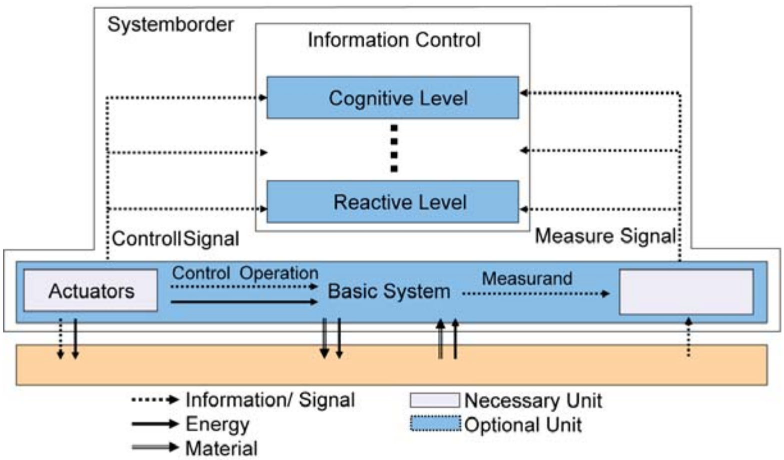

Fig. 1: Reference architecture of cognitive technical systems

The quintessence of cognition according to Strube [1] is *"... the sum of mental representations and processes ..."*. This means the notional digestion of the perceived. Analogically, cognition intervenes between the reception of stimulus and behavior. This definition together with the properties mentioned eventually results directly in the cybernetic motivated control loop architecture, as it ultimately forms the basis of mechatronics [2]. From the technical point of view are a series of sensors and adequate actuators integrated in an overall system, which are coupled by an appropriate information processing system. Perceptive properties correspond to the perception of the environment as well as of the technical system's own inner conditions. Motor-functional control, so the generation of actions for the purpose of modifying or manipulating the environment must be assured by the system of actuators (Figure 1) [7].

Information processing in cognitive system has to assure the original cognitive properties memorizing, recalling, thinking, and solving problems. For the technical realization, these properties partly provide a much greater challenge, since data and information received from the environment and from the system itself have to be reasonably interlinked with each other and memorized in a knowledge database. Comparing data and knowledge from the database with data gathered from the situation and the evaluation of that comparison is equitable with thinking. The so effectuated deciding situation finally results in problem solving. In this connection, the technical system's abilities need to be taken into consideration, which are characterized by the overall structure, the arrangement of sensor technology, and the actuator system's capacity to act.

From this description finally it becomes clear that the integration of cognitive abilities actually means an enhancement of the mechatronic thought. Whereas in the mechatronic system, a certain stimulus (sensor data) is always rigidly coupled to a predetermined reaction, are in natural cognitive systems like the human being these couplings between sensory perception and action no more rigidly coupled but modifiable. That modification of adaptive and thus indirect couplings adducted by cognition is implemented by learning. Non-cognitive regulations are consequently not adaptive and from the technical point of view, the situation of inflexible programming is thereby described.

Interesting in this respect is the circumstance that cognitive abilities in a system always build up on purely reactive systems. For the human being, these are reflexes such as regular breathing, feeling hungry, or shrinking away from fire and hot objects. These reactive abilities prove to be indispensable for survival. Cognitive abilities always require a reactive base system, which for securing the system's existence in no case may be bridged. So from the technical point of view, the high development status within mechatronics is a very good starting basis for extending technical systems by cognitive abilities. For the extension of a reactive system by cognitive abilities, a multi-level approach is recommended, which is geared to the principles of cognition science [Stru96]. This approach implicates three levels. On the reactive level, an associative level builds up that forms the new interconnections between actuators and the sensory system on basis of repeated linkage. A cognitive level assumes the deliberative function. New behavior patterns are based on mechanisms, which define and evaluate consequences for actions (Figure 2).

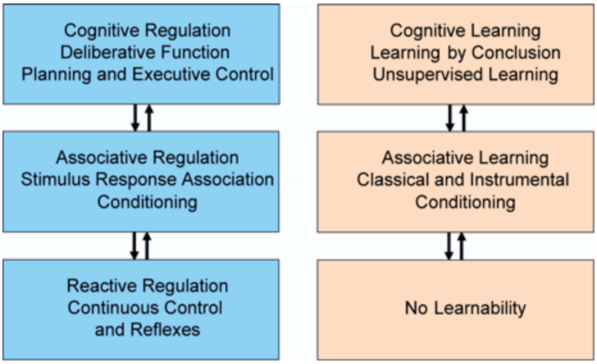

Fig. 2: Learning stages following the three-layer model

In cognitive sciences, three specific features are named for cognitive systems [3]:

- The active integration into the environment and thereby the ability to exchange information with it
- The representation of system-relevant data of the environment and of the own structure for the flexible and adaptive control of actions
- The learning and anticipating aptitude of the integrated information processing system.

All three features still today present a great challenge for the technical realization. In the focus of this article however is the third point, which shall be treated more closely in the following. Thereby it is not the point to explain specific questions of Informatics or artificial intelligence in connection with learning. The emphasis of this article is rather on the aspects of embodiment. The objective is to describe what aspects are necessary for architecture approaches to support the learning aptitude of technical systems.

For that purpose it is first of all necessary to briefly present the term of learning from the viewpoint of psychology and cognition sciences and from the viewpoint of pro-technical research in the field of artificial intelligence.

3 General Structuring of Learning

3.1 Forms of Learning

In psychology and cognition science, the term of learning is explained by very different definitions, each of which putting other aspects in the foreground. By the term learning, commonly the acquirement of new knowledge respectively the restructuring of knowledge already acquired is understood [4]. In connection with the description of cognitive abilities, learning is to be considered as the key, by which breaking up rigid sensor-actor chains succeeds. When learning is considered as a process, a procedure is described by it that enables a system to handle the same or a similar task better in future.

As an application-theoretical framework for the modeling of cognitive as well as non-cognitive controls of behavior and actions, Strube [1] suggests a three-layer model (Figure 1). The lowest level is formed by the non-cognitive regulation, for which reactivity is ensured by simple continuous control systems and feed forward control loops. On this level no learning takes place, sensor-actor couplings are quasi definitely preprogrammed. The cognitive level is the highest level in this model. From the view of cognition science, it is characterized by intention management and planning and action control. This is basically equivalent to learning by insight that means, new knowledge is achieved by logical drawing of conclusions from already existing knowledge or by encoding new information. This type of learning undoubtedly is the greater challenge for the technical realization, since attitude changes occur uncontrolled in most cases, resulting from spontaneous recognizing of structures of a problem being confronted with.

The associative interface level is connected with associative learning, also named conditioning. In conditioning, successfully performed reactions to recurring stimuli are recognized by the system and memorized as definite und stimulus-reaction couples [5]. From the view of cognition science, hereby is distinguished between classic conditioning (Pawlow reflexes) and instrumental conditioning. While with the first form, a new conditional stimulus is learned to a reaction already having command of, with instrumental conditioning new behavior patterns are acquired by trial and error.

From the description it becomes clear that classic conditioning can comparatively easily be integrated into technical systems by gathering extensive sensor data, which then have to be scanned for patterns and repetitions. Instrumental conditioning however is much more difficult to be integrated into the technical system as here the feasibility is required that the technical system can determine internal objectives and act motivated. In addition, a possibility for self-regulation is required for the technical system.

The effectiveness of learning in the upper levels also very strongly depends on the abilities of the technical system. These result from the purpose of the system, its basic implementation in the domains, and its integration into an overall system. So the abilities are characterized by the embodiment.

3.2 The Learning Process

Decisive for further considerations is that learning represents a process, which can be promoted by system architecture. Thus the learning process can be described as a property, which is essential to be developed, not a feature that can be solely defined e.g. by a source code or the configuration of hardware. Learning aptitude in a technical system is always based on the entirety of features. When considering the process of learning closer, sub-processes can be identified: information need be gathered and compared context-related, patterns and regularities are to be recognized, conclusions must be drawn, resulting actions and operations need to be evaluated, and memorizing capacities are to be utilized to make knowledge recallable (Figure 3).

The learning process represented can be integrated into the architecture of technical systems. As input for the learning process, a stimulus is provided by the system. The output is depicted by a modified behavior or a newly learned action that serves as triggering for the actor system and therefore needs to be adjusted to the same. In case information cannot be perceived or memorized, the learning process breaks up unsuccessfully.

Within this learning process, now also both forms of conditioning can be fixed to concrete partial steps within the learning process. Since classic conditioning primarily relates to the evaluation and analysis of sensor data, it can be considered as rather input-oriented. However finalized is the learning process not until the success of the resulting action is verified. From the technical viewpoint, it is imperative to construct the sensor technology so that relevant data from the environment as well as from the system itself are gathered as comprehensive as possible and in an efficient form. Then problems of sensor data fusion but also of recognizing patterns stand in the foreground.

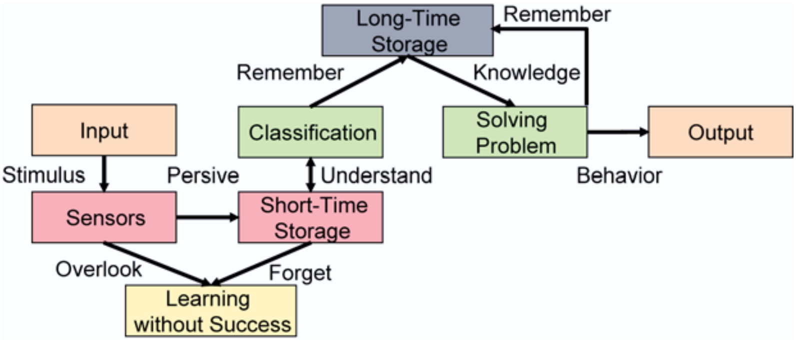

Fig. 3: The learning process [6]

Instrumental conditioning as basis for purposeful non-instinctive acting acts on the assumption that each action is followed by a consequence. Compared and evaluated are now action-consequence combinations for the acquisition of new behavior patterns. Crucial thereby is that on the one hand that behavior patterns are followed by a consequence, which is agreeable if that behavior contributes to problem solving (amplification), and disagreeable if that behavior is inadequate for problem solving (punishment) [4]. Theories on reinforcement learning are already successfully applied in information processing in neuronal networks. At the same time, this form of learning is rather output-oriented. In the technical realization, on the one hand actuators with reactions as fine-adjustable as possible are required. Actions can thereby consist of fine-adjusted simple operations, but also result from a sum of operations. Finally also here need results to be compared to the system's objectives to enable evaluating of operations in the context.

The highest form of learning, learning by insight, integrates the learner, in this case the technical system, stronger into the learning process by developing new behavior patterns through observation and consequential emulation. Important functions are thereby abstracting and the drawing of conclusions. The form of learning is very much depending on a high-performance information processing system, but also necessitates the technical realization of attempts of self-regulation and motivation.

4 Conclusions for the Designing of Technical Systems

From the description of forms of learning it becomes apparent that in addition to the description and evaluation of the behavior of technical systems also motivation and situation represent important components, which need to be describable to enable implementing learning aptitude in technical systems. The technical system's behavior is always to be interpreted in the context of the respective situation. Belonging to the situation description is in addition to the description of the environment also a description of the technical system and its present inner conditions. Already the description of the environment for cognitive technical systems is very complex due to the desired autonomy of such systems, since an unstructured, at least semi-structured environment is to be assumed. Acting as appropriate to the situation is only possible if the system is able to acquire all relevant environment parameters to the extended possible and to bring them into an applicative context. Here the system needs to find its own reality, which naturally is independent from the one of the developer, since technical system and developer are working with different sensor equipment. Therefore, methods for objectifying are inevitable for the situation description.

That objectifying undoubtedly represents a great challenge for the developer, since he or she quasi has to put him or herself into the technical system in a way where he or she sees "with the eyes of the technical system". Adding to this is the fact that the purpose of the system of course is the starting point of all considerations for development, but the behavior, so the way of reaching the principal objective, comes stronger to the foreground. Along with that goes the consideration of a multiplicity of subordinate targets that cannot be hierarchically coupled together anymore, but appear as a multiple target system with heterarchic character. That phenomenon cannot be handled by classic logic anymore, here the use of poly-contextual logic is offered.

In addition to these aspects, questions of self-regulation gain very much in importance. Self-regulation however comprises three more prerequisites a technical system has to fulfill: [4]

- The cognitive technical system must amplify itself and is consequently subject and object in one
- It must be able to freely dispose of the amplification (which requires an own view on the environment and inner conditions)
- Amplification does not happen by coincidence but after the occurrence of specific behavior patterns that are to be described by the system itself.

The two other processes of self-regulation are self-observation, so the extensive verification of the own behavior, and self-evaluation. Self-observation includes on the one hand that the technical system is informed about its current inner conditions, which today may be assumed as state-of-the-art. Here is the automat theory available to the developer as a high-performance method for interpretation respectively description of inner conditions. In self-evaluation, the behavior observed before is compared with performance criteria from earlier experiences. Those performance criteria are at first to be determined by the developer, but then need to be concretized and refined by the system.

The integration of motivation into cognitive technical systems implies that such systems have mechanisms of self-amplification. By self-amplification, the behavior is either continued or in case of nonconformity with the existing performance criteria, it is necessary to build up new behavior patterns. Building up new behavior patterns is based on logic categories of learning according to Bateson and Goldammer [8], which this article cannot dwell on.

The term motivation is derived from the Latin word “movere”, which stands for moving. The meaning of it is that the behavior of a cognitive technical system is moving towards a looked-for target. So motivation can generally be understood as a readiness for behavior or acting, by which the own system activities are oriented towards a certain target. Motivation is an indispensable prerequisite for learning additional new behavior patterns or changing them. Then together with the definition of needs that result from sub-ordinate targets of the cognitive systems, strategies can be developed, which enable coincidental exploring and so learning by trial and error at all. Leads for amplification can be found on this basis, which mean intensifying the required behavior. As difficult proves to the developer to find appropriate motives, so to answer the question what a technical system generally wants, on the basis of which then questions of self-regulation as well as of behavior control can be clarified.

A basis for the description of human behavior control is provided by the pyramid of needs according Maslow [9]. A transference to technical systems is absolutely possible for the lower steps while the upper steps, which are characterized by quality of life and self-realization in contrast require a technical interpretation. If a technical system actually follows an intention, it must have a certain intentionality, which means, inner conditions have to be able to relate to something definite. This aspect is satisfied the BDI architecture known from software development, which is applied by software agents. An interpretation in the sense of overall structure design of technical systems is necessary here also.

5 Summary

To enable integrating cognitive abilities into a technical system, not only a high-performance information processing system is required, but also it is important to incorporate also the structure of the technical system into considerations. The importance for the possibility of implementing motivation and self-regulation into a system was demonstrated. To enable the adaptation of behavior patterns in line with the technical prerequisites, a potentiality to determine and to evaluate consequences for the system is required. Presented within the scope of this article were only approaches, the concrete detailed formulation of individual methods is subject of further research.

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New Perspectives on Design and Innovation

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1 New Challenges

Industry and society face a range of new challenges concerning innovative competences, methods and approaches, in order to develop new products and systems on a competitive basis. These are challenges which ensue from the dynamics of change stemming from technology, markets and society in the new globalised context.

- Market offerings and products are increasingly associated with immaterial elements. But these new types of 'extended products' are often left to be handled by methods and approaches based on earlier industrial practices.
- Increasing demands for individualization and customization of products are being called for, along with demands for short response time and dynamic restructuring of companies according to new market demands or technological opportunities.
- Globalised manufacturing and market creation foster new demands for business development and innovation in a context of global networks and value chains. In this context, company developments have to reflect employees with a diversity of attitudes to intellectual challenges, sustainability and responsibility.
- Societal demands on improved effectiveness in use of resources, incorporation of environmental concerns and concerns for working environment and ethical aspects along with improved competitiveness. Responses to these challenges will increasingly demand for product innovation and the development of new business concepts.

- Innovative activities can no longer only be supported and solved within dedicated development departments, but have to incorporate a multiplicity of competences and business activities. Accordingly, company organisation and new collaborative patterns and competences cutting across established departments for development, research, marketing, manufacturing, strategy and technology will be needed.

New structures of cooperation in product development and innovation following these new challenges also demand new competences from engineers. Traditional training in natural sciences and technical disciplines with supplements from social sciences including ethical, social, economic and management issues can not in itself provide these new competences. As a consequence, new engineering curricula have been developed within design and innovation at a number of technical universities in Europe and the US. In order to support the development of new competences and enable industry in meeting these challenges the development of new methods, concepts and understandings based on research and exchange of experiences between research and industry are needed.

Under the label of 'user-driven innovation', it has been pointed out in Denmark that increased understandings of customers' latent needs and preferences could become a new driver in the innovation processes in Danish companies. Users have always been present in the product development processes in some way or other. So the question is, *how* new insight in use processes and users interaction with products can improve innovation processes. In this paper it will be stressed that user *oriented* innovation involves the inclusion of *many sources* of knowledge on *users,* but *also* knowledge on *markets* and *technology*. The paper hereby aims to qualify particular lackings and shortcomings with the simplistic underpinnings on which the notion of 'user-driven' innovation is built. The paper elaborates on how a broader, yet more nuanced understanding of user *oriented* dimensions may contribute to the tight coupling between product innovation processes in firms and their orientation towards (new) user and market domains.

The paper will reflect on research perspectives dealing with the incorporation of knowledge on use, users, customers and market in the entire innovation process. The point will be made that the support of user oriented innovation processes will have to deal with development of new approaches, methods and competences as well as methods for their implementation. The challenge will be to change existing perspectives on users in the product development process which calls for a reconceptualisation of the entire product development process emphasising the staging, framing and management of innovation.

As a response to the new demands for developing industrial and societal competences in innovation, DTU has developed a research program in design and innovation in the context of the broader Danish research consortium of Centre for Innovation in Product Development (CIPU)[1]. The aim of the research program is to strengthen the capabilities and competences of industry to develop new products and systems that can improve prosperity and welfare in society. The idea is to assist industry in handling these challenges by developing a new conceptual framework for staging and managing design and innovation and develop and implement new methods and approaches in product development. The ideas presented in this paper reflect the contributions of the authors as part of a broader collaboration between colleagues at the Department of Mechanical Engineering and the Department of Manufacturing Engineering and Management at DTU.

2 Innovation in Networks

The increased focus in product development on user adaptation, market orientation and business creation is an important challenge to be taken up in product design and innovation. But, at one-sided focus on users and markets may risk leading to a decoupling from those of the firm dealing with technological development and innovative processes. However, the idea of contradicting a technology-driven and a user driven innovation is misguided, and grounded in an old-fashioned notion. Firms are being confronted with the complex challenge of having to combine technological and science-based knowledge for new products and processes, with knowledge about users, user situations and markets. A narrow focus on technology alone entails the risk of developing products, which are at best, difficult to market and thus entail a significant economic risk for the firm. A focus on users and their expressed wishes can be an important means towards creating new markets. Yet, a narrow focus on known users can potentially turn out to be extremely conservative in a product development situation. Technological options otherwise potentially may open up for new applications and new user profiles. In such a situation, strong visions (about future markets and use) and technological ventures become necessary, in order for the firm to succeed in an innovative breakthrough of a more long-term character.

[1] CIPU is the result of many years' of industrial and academic collaboration towards a nationwide campaign for innovation in product and service development. Read more on www.cipu.dk

The issue of translating and combining diverse sources of knowledge and insight into constructive and working solutions is not resolved simply by firms gaining access to users of their products. Anthropologically informed user studies may make knowledge and insight about users available to the firm's development function or marketing department. Video recordings of the use of medical products in use situations can, for instance, yield unique insight into use practices. But there is a significant challenge related to getting this type of knowledge and insight to play an *integral* role in the medical and the evidence-based research tradition. Insight mediated through video recordings, etc. must be further treated and configured into the established as well as innovative practices of the organisations, in order to play a significant role in the firm's decision-making process.

In order to manage this type of challenge, there is a need for new methods and approaches as well as new ways of organising these methods in innovation processes. Research into design, product development, and innovation points to a diverse range of product and user-related dimensions regarding knowledge, concepts and approaches, which must be taken into account. There is a significant need to further develop practical, analytical and methodological approaches utilising more profound perspectives on users throughout the entire development process.

There lies a significant challenge for firms in developing their competences toward organising the innovative interplay between the diverse constellation of actors and specialisations, which enter into innovative processes. How can rather different groups of users with different perspectives, bases of values and cultures enter into an innovative interplay with the development departments of firms? Research environments can have vague, or at best, rather superficial conceptions of the application of their know-

ledge and insight when it comes to concrete product areas. Which, and just as importantly, how, can research-based knowledge be integrated in a process, where users and market orientation also play a central role in the process of product innovation?

Products will increasingly have to function in a complex and heterogeneous network of relations entailing a range of actors, bases of knowledge and practice, as well as association with other artefacts. It is indispensable for innovative processes that creative and successful translations of attribution of meanings toward the product are achieved in relation to actor relations. Innovation is an open process, whose result cannot be given á priori (at least without a set of qualifications), and which renders space of adjustment and change in any local context of application. Innovative processes are a result of the work of synthesising, through constant experimentation and engagement with the involved set of heterogeneous relations (between technologies, users, other actors, costs and visions, etc.)

It is no longer sufficient to focus on the capability of the individual department, e.g. that of product development. Coordination often involves distributed tasks among product development, manufacturing as well as other functional divisions of expertise ranging from sales, marketing, environment, human resources and technological research and development, foresight as well as knowledge on product usage and maintenance. The establishment of new industries, business areas and markets will often demand a substantial exchange of knowledge and information among manufacturers, customers, qualified (knowledgeable) users, authorities and other institutions. How is such interaction organised, so that innovative solutions are encouraged for all involved? These challenges become all the more clear when the issue deals with the development of new products and markets through dialogues between users, firms and suppliers in global business chains.

3 User Configurations – Use Practices

A range of methods are available for companies to improve communications with users and to depict user preferences. These include description of use situations, identification and priority of user needs as well as the broader analysis of user networks, user contexts and the more in-depth work with user ethnographies. The term ‘user ethnographies’ includes the translation of user observations into design spaces in order to challenge the designers’ conceptions of users. User-driven innovation should not just focus on users and their preferences, but on the way users are ‘created’ in the design process. Akrich [1] has pointed at the different perspectives and pictures of the users that can be found in different departments (design, manufacturing, sales, marketing) and among different professional groups in a company. These departments may have different ‘sensors’, tools and ‘observatories’ in order to understand and work with knowledge on users and markets. The implication being that diverse interpretations of user preferences compete and that the resulting configuration of users may act as an invisible hand instead of being the outcome of conscious choice.

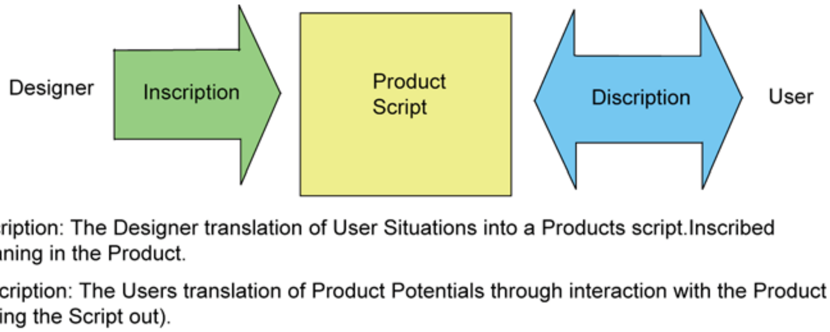

Fig. 1: Inscription, script and description

Von Hippel [17] has provided a range of examples on how certain users (lead users or more or less professionalized communities) can take on a role as designers and interact with product development in companies. Following from von Hippels research, the question may be phrased, as to how lead users may be identified at an early stage, where the product idea is far from developed and the users are unknown. With the term of co-construction of products and users, it is shown, that users are being constructed along with the development of products [15]. Research within innovation economy and sociology of technology [16] has pointed at the complicated interaction between design and use as two different actor worlds, and that appropriation of products and creation of markets for new products depend on the development of a stable use. The interaction between design and use may be seen as a learning process, where heterogeneous relations between (new) actors and objects in product design and use become configured and aligned into stable practice and sense-making. The study of use practices has discovered that important sites for co-construction should include a broad network of intermediate and 'end'-users. In the food sector, for example, this point is rather obvious and can be illustrated by the user-producer chains from soil over farming to industrial processing, packaging, distribution and reprocessing and serving. Product development may involve larger or smaller part of the chain but will inevitably include co-construction of products, business relations and user-producer relations.

Also the interaction between development and use may vary along the 'biography' or the 'product life' of a product. Synthesis oriented approaches – like concurrent design or integrated product development – to product development [11] suggest an array of methods to be applied along a products life cycle from idea over conceptualization and product design to manufacturing, distribution, sales and scrapping, recycling etc. In this perspective, it becomes clear, that markets, prices and costing are deeply interwoven with the creation of supplier-user networks in the development of product-service systems. Also new approaches in conceptualization [10] may favour user orientation by emphasising analysis of user contexts and scenarios for user interaction with artefacts in line with integration of knowledge from engineering practices, technology and a range of other sources.

Situations of interpretative flexibility, where issues of pertinence concerning a product varies among relevant actors and over a span of time [2] may interchange by closure and stabilisation processes turning a volatile product into a stable market situation, and vice versa. Other important concepts in this line of research would be the domestication of products emphasising the role of scripts and how designers inscribe meaning into the product and how users 'describe' and translate these meanings. It is a challenge for user driven innovation to study these phenomena and to develop methods being able to support companies in integrating this knowledge in the innovation processes.

The multi-actor perspective on design and innovation points to the negotiated character of design and innovation processes. The design space can in other words, in principle be informed by a broad range of concerns. These stem from a multiplicity of actor-positions, from the product design and manufacture, to its distribution and specific contexts of use (and disuse) as well as to disposal or possible 'reuse'. Compared to the traditional characterisation of the relative passive nature of the 'diffusion' of products in society following otherwise active research and development initiatives taken on by the firm, more recent social and cultural studies of technology have focused on the 'use'-end of innovations. Here, the very active interplay of products and social actors come to light, in situations of appropriating innovations in their specific contexts of use or other forms of engagement (such as distribution or discard).

This theoretical perspective on technology appropriation known as 'domestication' has its origins in studies of consumption (Silverstone). Here, the cultural meanings play a role in how technologies are appropriated, objectified, incorporated and converted in the everyday practice and become an integral part of the economy of the household. At the same time it transforms the very context which it enters into, through this process of integration along practical, symbolic and cognitive dimensions. What is of interest in this regard, is that products may be domesticated *differently* in different contexts of use, i.e. that the product or the innovation do not *determine* what the *one* characterisation of use may be. Different contexts, thus point to different dimensions of the product quality or properties. The very unit of analysis concerning the domestication of technology is thus broader than household(s) and may be extended to national differences, institutional difference, as well as various stages of the product life cycle – where different actors (‘users’, ‘regulators’, ‘promoters/facilitators’, etc.) have different context of engagement with the product.

This form of analysis also implicates the ‘market’ as a site where multiple strategies are enacted by various actors, through their respective sense-making of the product in relation to their context. Such a view on product-market relations serves to sensitise actors on the scene (including the firm and its innovators) toward how market conditions may be differentiated, problematised and provide insight into the firm’s standing and room for manoeuvre. Market concerns and insight into user issues are thus aspects which have strong bearing on what firms can undertake in terms of product development and innovation.

The conception of products as well as of services and systems encompass a range of material, social and symbolic aspects of artefacts. This means that materialised products entail an object-world which refers to visions of use and users which extend beyond the products’ functional aspects, as is traditionally construed. This object-world covers expectations, interpretations and visions tied to the product. In a corresponding manner, the expectations tied to immaterial products will often implicate the existence of material artefacts, which render the immaterial products and their use possible and meaningful.

In this scheme of things, design deals with the creation of new actor-worlds and new arrangements and orderings of social and material relations of a hybrid character. Heterogeneous elements of actors, artefacts, visions and business strategies, but to name a few, make up these hybrid orders. The staging of such ordering of processes and the bridging of boundaries between local and global perspectives are crucial challenges for the managing of innovative processes. This inter-disciplinary perspective serves as an indispensable guide in the development and consolidation of a new integrated discipline and perspective on design processes and innovation.

4 Innovation and Design as Social Processes

The DTU program takes its departure in the understanding of design as a sociotechnical process involving processes of synthesis. Our contribution to the understanding of design as a sociotechnical process draws upon the theories form the new sociology of technology as well as cultural studies of technology. Here design is seen as the outcome of an interaction between different players, with their different knowledge and perspectives on problems to be solved and their different approaches and preferred solutions. Recent studies inspired by a social science approach consider engineering design as a collective and social process of creating material artefacts [5] and innovation is seen as a social process that entails a change in a network of social relations. Creation of networks and changes in relations between actors in networks are seen as the outcome of translation processes defining the content of the network (the idea, fact or product it embraces and support) in a mutual process. Innovation is thus about changes in some or all of an existing set of identities, expectations, beliefs and languages. This broadens the scope of the design process to include the attempts to order and structure the object worlds including the social interactions and user interests involved, but in an interactive and reflexive process where the choice of participants and representations is crucial for the outcome [4].

"Claiming design is a "social process"…means that participants in design processes must spend time and energy discussing, listening, proposing, and arguing with one another about their respective proposals which will ultimately fix the form of the design. This sort of negotiation and exchange is hard work." [4] This would also include debates on priorities concerning the kind of needs or problems among potential customers a company should engage in, and the kinds of solutions to be preferred in product development. Priorities that can not be reduced to management decisions, but which often engage a range of people beyond cross disciplinary product development teams.

Concerning the understanding of innovation, we allude to Pavitts 'general framework' [14]. Here "Innovation processes involve the exploration and exploitation of opportunities for new or improved products, processes or services, based either on an advance in technical practice ("know-how"), or a change in market demand, or a combination of the two" [14]. Innovation is inherently uncertain, given the impossibility of predicting accurately the cost and performance of a new artifact, and the reaction of users to it. Pavitt points at the translation of knowledge from a variety of sources like research, user practices and markets into working artifacts as one of the most important innovative processes.

The Actor-Network Theory (ANT) approach [6, 13] provides a theoretical foundation that defines the generation of ideas and knowledge and the development of working artefacts as network building processes. Creation of networks and changes in relations between actors in networks are seen as the outcome of translation processes defining the content of the network (the idea, fact or product it embraces and support) in a mutual process. Michel Callon [6] describes translation as the following set of actions: problematisation, interessement, enrolment and mobilisation. Through the translation processes, if they are successful, facts and technologies are made strong and durable preconditions of further action. Network building processes are important in the staging and management of design processes, in the creation of organisational spaces for design and in the framing of meaning and the generation and selection of ideas for product development.

Notions such as markets and technological potentials are seen as the outcome of translation processes and not as predefined concepts or facts we can go out and look for. Through the translation processes, if they are successful, facts and technologies are made strong and durable preconditions of further action. Network building processes are important in the staging and management of design processes, in the creation of organisational spaces for design and in the framing of meaning and the generation and selection of ideas for product development.

5 Shortcomings of Linear Models

Despite the need to focus on processes and content in design processes and innovation, the dominant methods and approaches do not address these issues in an adequate way. The widespread 'stage gate' models predominantly focus on minimizing the risks involved in product development. It does so by defining tasks and conditions for organisational investments of resources and contributes procedures for project evaluating and killing of non-performing projects. Emphasis is on commissioning and evaluating projects while the generation of ideas are left to the task of selecting of team members and decisions concerning the composition of cross disciplinary or departmental teams. Here, established departmental interests and organisational politics easily make the stage gate model a contested terrain of inclusion and exclusion of players and perspectives. From an organisational and management point of view, these are very important features, but they do not necessarily contribute to the translation of knowledge into working artifacts. Little attention is paid to processes of identifying relevant knowledge or to the content of ideas and their potential alignment with company strategies.

The 'front end' activities are often more important for the generation of new product ideas and product conceptualisation than the selection of team members after project commissioning. But the front end activities are normally not included in the stage-gate model and are of a more fuzzy nature. Also Cooper, one of the fathers of the stage gate models, indirectly admits these shortcomings in stating that "[T]he keys to new product success often lie in the up-front or predevelopment activities. Unfortunately, these early stages receive little time, effort, and attention." [9]. Based on these challenges, many companies experiences that 'stage – gate' models falls short in offering sufficient guides and tools.

An example from industry could illustrate the point. The hearing aid industry is an example, where strong disciplines from audiology, materials engineering and hardware people have had a major role in early phases in product development. In the linear stage model, the front end activities often have been perceived as defined by knowledge generation and input from longer term research or technological development. This is also reflected in the traditional modelling of product development, but increased dynamics in knowledge generation concerning user behaviour, market generation and technological knowledge challenges the linear model. Instead, the product development process is increasingly pictured by the industry as network processes involving heterogeneous players with a range of diverse perspectives on what constitutes a good working hearing aid. Here the stage-gate model is treated as a 'machinated' way of organising and has accordingly been confined to a certain but limited role in the product development process.

6 Sociotechnical Spaces

One of the key challenges in innovation processes is to transform knowledge and ideas concerning technology, users and markets from departments and groups within the organisation as well as from the outside world in a useful way. Design processes and innovative activities take place mostly as activities which span across a range of organisational departments or functional divisions, where these often would have different perspectives or emphases on design. The perspectives on design and innovation, within the organisational frame of such activities, also often vary over time together with shifting projects and political agendas. For these reasons, it is difficult to unequivocally localise, where in the organisation, or in which network of actors, the responsibility of design and innovation activities are (or should be) placed. Managing innovation, design and product development will increasingly entail the arrangement of interaction between actors, competences, artefacts and organisational agendas involving programs of organisational change which bear upon product development activities.

So there is a significant challenge for firms to organise the activities of design and innovation, particularly in the early, informal design stages. For many firms this will include breaking with established ways of thinking and organisational mindsets, without compromising the established organisational knowledge and competences giving the firm competitive advantage. The staging of innovative interactions within or around a sociotechnical space can strengthen and bring about new innovative performances and the ability to change. Innovation in product development can be strengthened through making use of existing space(s) and an increased ability to create new spaces for design and innovation, through the reorganisation of interaction among established spaces.

Where the processing of knowledge within a certain knowledge domains may be guided by established methods, practices and rules of thumbs, the exchange of knowledge across specialised domains seems much more challenging. Carlile [7] describes difficulties in transferring knowledge in a new product development across the specialised functions of sales and marketing, product design, manufacturing engineering and production in a US American supplier to the car industry. Innovative solutions demand a transformation of knowledge across functions where established understandings and knowledge practices within the single domain are challenged.

Actor-Network Theory points at the translation of knowledge from a variety of sources as the main process in the constitution of sociotechnical spaces for product idea generation. The point is here, that multiple players are involved using a variety of often conflicting interpretations of problems and solutions based on the specific working of a network of people, objects or machines as translators. A question is whether and in which meaning these translations can be managed and how they contribute to the constitution of a sociotechnical space for innovation and product design with its specific inclusion and exclusion of the content of ideas. The notion of ‘socio-technical space’ as suggested by Clausen and Yoshinaka [8] is intended as a contribution to understand the distributed character of sociotechnical complexity and its management. In a socio-technical design spaces social players interact with one another, with technological artefacts, and management concepts and technologies. A similar concept concerned with strategic aspects of the development for the future technology and markets emphasising the role of visions in the structuring of networks is the concept of ‘arenas of development’ proposed by Jørgensen and Sørensen [12].

The particular configuration of a space includes and sustains some actors, their agendas, and particular frameworks of action within it, while leaving others excluded. A socio-technical space can therefore be seen as a target for diverse political concerns and perspectives in organisations. A socio-technical spaces approach allows not only for the potential opening of spaces for scrutiny and exploration, but also for the bridging of ‘spaces’ otherwise rendered distinct and without immediate or obvious relevance to one another. In this light, the facilitation of particular views and combinations of knowledge and can contribute to innovative processes in technology design, implementation and change.

The sociotechnical constitution of these spaces and the contradictions and challenges these poses for managing are increasingly becoming an organisational issue. In a situation where no single actor, ingenious inventor, brilliant designer or company founder can act as interpreter and translator of trends in societal needs nor can have an overview of specialized generation of knowledge, companies have to rely on multiple translators. Product innovations have to reflect a broad range of potential sources for inspiration, situations from use, future environmental demands, ethical debates as well as the more traditional sources from marketing, specialized technology or research departments, universities etc.

7 Challenges for Management of Innovation

A company developing and supplying equipment for the medical sector has developed a strong position in the design and manufacturing of their products through a long term strategic orientation towards user needs and inclusion of user experiences with their products. The company has chosen to translate the user experiences through professional groups of intermediate users, in this case the nurses active in providing care for the end users. This make good sense as the stomi patients are a very weak and vulnerable user group being dependent of the care and advice concerning the qualities and use of stomi products. A working socio-technical space including annual meetings and formalised exchange of knowledge concerning use is constituted through the interaction between design engineers, stomi products and the communities of practice established among the nurses.

But, the choice of translator also has consequences for the innovation process. As a result of the long term interaction, established practices of knowledge exchange favours incremental improvements where especially the nurses stick to what they know is working. Also company strategy may become dependent of and adjusted to incremental innovations. More radical innovations in product ideas are thus not likely to appear through this channel of translations of user needs.

Other examples point at other established translations. Sales and marketing departments may have developed methods for translating user needs based on market research favouring the countable numbers. Users are here reduced to statistics on sales numbers, prices and user categories described in terms of market segments. This is a very different 'translator machine' as the one of a community of practice or of a service department being able to actually meet the users. If we take the specialist departments concerned with environmental questions or those concerned with trends in materials, audiology or medical specialities it is obvious, that they again offer very different translations of trends in knowledge, technological potentials or market trends.

Figure 2 illustrates how socio-technical spaces may be constituted through a mindful selection of translators of diverse knowledge domains.

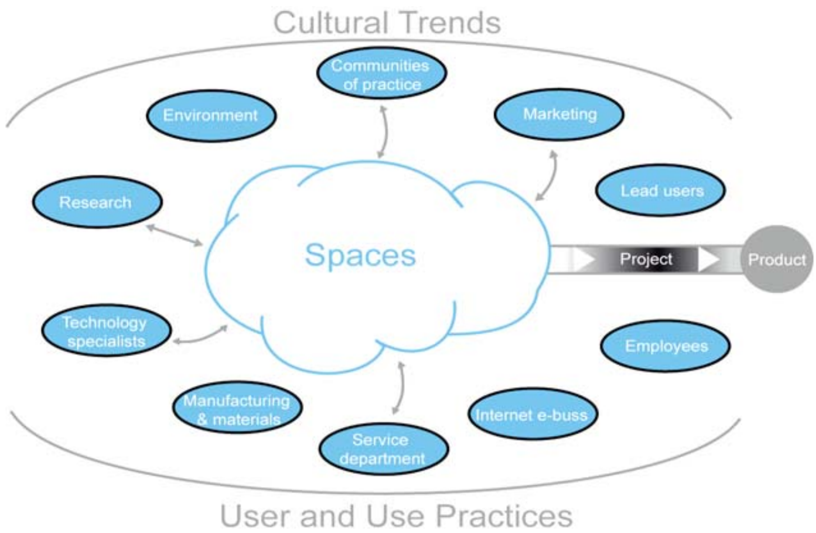

Fig. 2: Staging of early phases in product design

A key challenge for management of a product development is how different translators of users, markets and technology may be identified and coordinated throughout the innovation process. This seems to be a new challenge, yet to be taken up explicitly as a management issue in new product development. Companies instead often rely on implicit and emergent strategies. We therefore suggest in this paper, that the development of new concepts and practices regarding the role of translators are relevant for the management of design and innovation.

The spaces approach keeps focus on the choices concerned with inclusion and exclusion of organisational players and the mutual translation of players and content of change. Accordingly, we may suggest management to develop competences needed for the identification of socio-technical spaces for interaction and translation and how they work.

The concept of socio-technical spaces should help analysts and practitioners to identify spaces and the possibilities for 'spacing' and 'staging' of design activities and change processes. These may entail the creation, configuration and reconfiguration of actors and actants, the definition and redefinition of boundaries and the bridging of diverse spaces as processes of translation and network building, etc.

Another management task would be to identify, evaluate and choose relevant translators. The construction and selection of translators may be an important handle in the staging of selective mechanisms. A debate on the workings and role of translators should promote a reflexive content focused debate of visions and ideas for product development. An example of an important concept that should be further developed in order to analyse and characterise the role of translators would be the notion of boundary objects between knowledge domains.

Finally it is important to point at relevant tools and strategies for the creation of change in established organisational practices. Many barriers for innovation are construed through organisational politics and the views and perspectives being either openly articulated or just practiced in silence. Here, design approaches or management concepts can act as the new change agents together with mindful organisational players.

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Future Trends in Product Lifecycle Management (PLM)

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Abstract
Over the last decade PLM has become one of the key technological and organisational approaches and enablers for the effective management of product development and product creation processes. The first part of the paper summarises the current PLM state of the art. The second part of the contribution describes the main expected development directions in PLM and shows some results from PLM research projects carried out by ITM Bochum in cooperation with different industrial partners.

Keywords
Product Lifecycle Management, PLM, Information and Process Management, Engineering Collaboration

1 PLM State of the Art

Over the last few years product lifecycle management (PLM) has become the central management approach in engineering in the manufacturing industry. As the PLM acronym was mainly promoted by ICT providers, the PLM approach is currently often considered synonym to an ICT system. Although the IT tools are important enablers for PLM, the PLM approach is much more than just a piece of software.

PLM is an integrated approach including a consistent set of methods, models and IT tools for managing product information, engineering pro-cesses and applications along the different phases of the product lifecycle. PLM not only addresses one single company but a globally distributed, interdisciplinary collaboration between producers, suppliers, partners and customers [1].

PLM evolved from the nineties' product data management (PDM) approach. While PDM was ICT driven and had a narrow focus on the ma-nagement of product data within product design, PLM has a management focus addressing all data, processes and applications for the entire lifespan of a product.

The quintessence of the PLM approach is an integrated data and process meta model managed by a database management system and a central controlled data vault for the storage of all created proprietary models and documents (e.g. CAD models, text documents), fig. 1 [2].

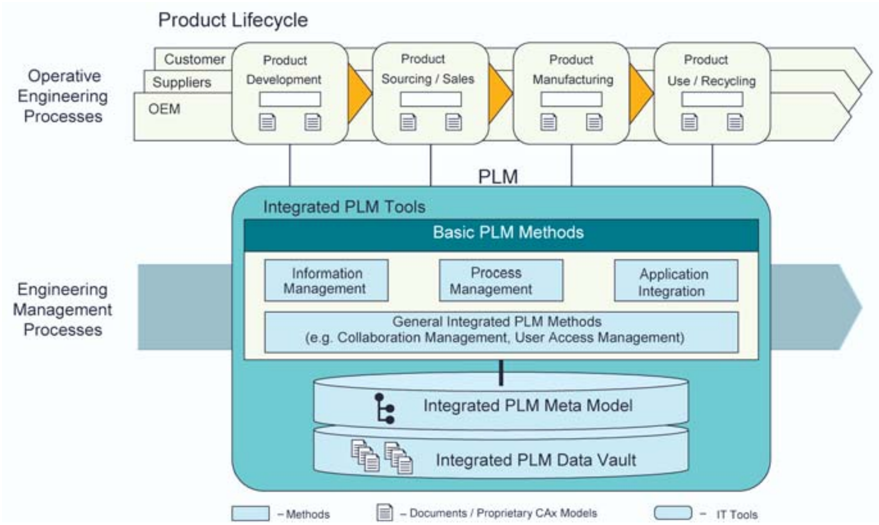

Fig. 1: Basic components of the product lifecycle management approach

Available PLM methods and tools can be clustered in three groups [3]:

- Information management (e.g. methods for identifying, structuring, classifying, modelling, retrieving, sharing, disseminating, visualising and archiving product, process and project related data).
- Process management (e.g. methods for modelling, structuring, planning, operating and controlling formal or semi-formal processes like engineering release processes, review processes, change processes or notification processes). The strong link between the different process stages and the resulting product models are covered by so-called configuration management methods and tools.

- Application integration (e.g. methods for defining and managing interfaces between PLM and different authoring applications like CAD, CAM, CAE and integrated enterprise software such as ERP, SCM or CRM systems).

In addition to these basic PLM methods and tools the PLM approach includes a set of additional general integrated PLM methods and tools such as engineering collaboration support, user access management and data analysis, reporting and visualisation. The described PLM approach is not a ready to use solution but rather a vision or a frame-work, which can be used as a reference for developing company specific PLM concepts and implementation roadmaps. After a few years of promoting their own proprietary PLM definitions and views, the majority of PLM providers now shares the shown long term PLM vision and offers various solutions covering parts of the described PLM methods and tools.

Commercial PLM solutions reflect the providers' different historical background. The current focus of all existing PLM solutions is in the support of product development activities. Usually the available PLM solutions feature generic and preconfigured templates for data models, processes and functions for specific domains of applications or industries. The strengths of available PLM solutions are the management of CAD models and technical documents, the support of engineering releases and change processes as well as their strong integration with CAD and ERP and data systems. The main weaknesses of existing PLM solutions are the poor support of product lifecycle activities outside the product development, as well as of integrating mechanic, electronic and software components. Another problem of available PLM solutions is their very high complexity and the necessary, huge customising efforts. In spite of intensive standardisation activities, general accepted industry standards for PLM meta-data models and for PLM processes are still missing.

Although the PLM approach is not new and a lot of PLM solutions are available on the market, only 8 % of companies have a clear PLM vision and extensively implement PDM/PLM systems. About 50 % of companies implementing PLM still are in an early implementation stage [4].

2 Expected PLM Developments

2.1 Overview

The existing, described PLM meta models, methods and tools offer a core platform for further PLM improvements, extensions and new developments. As PLM is a very complex, multi-layered and multi-disciplinary topic, a taxonomy of this multi-dimensional development space is necessary, fig. 2. This space considers following development directions:

- the general approach instantiation for different industries or application domains
- the considered PLM users/actors or partners
- the covered phases of the product lifecycle
- the supported process types
- the covered product types

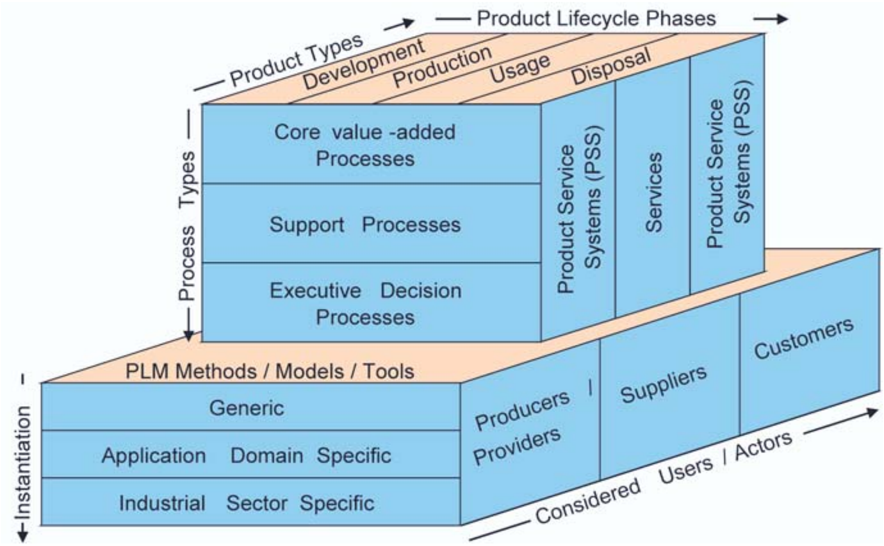

Fig. 2: Development space for future PLM methods, models and tools

The following sections describe the main expected trends within this development space, showing some examples from results achieved in research projects carried out by ITM Bochum, Germany.

2.2 Instantiation of the General PLM Approach

Current PLM solutions offer a lot of generic predefined templates for product meta-data and routine engineering processes. A lot of special templates are available for the automotive, aerospace and machinery industry. Future PLM applications will address other industry sectors like construction, pharmaceutical, textile, chemical or medical technology industries [3]. A lot of predefined templates for these new domains are expected in the next few years. Another trend is the adoption of the PLM-approach in non-industrial sectors such as hospitals, insurances or service-companies.

2.3 Considered PLM Users

The focus of existing PLM solutions is within one manufacturing company, including various distributed sites. Some recent research activities address the integration between producers and suppliers [5]. Future PLM approaches will also integrate development and service partners as well as customers within the early stage of the product lifecycle. An example for such a PLM extension is the project “Customer Centric PLM” [6].

The solution developed in this project allows customers to evaluate virtual product models during the development process of a new product by providing preferences, wishes and requirements to the producer (prospective feedback). During the product usage/operation the customer could also provide feedback on his experiences, his satisfaction with the product use and more improvement proposals, which can be used by the producer for the development of the next product generation (retrospective feedback). In the “Customer Centric PLM” project PLM models and methods were extended in order to integrate this customer feedback into the product development processes (e.g. change management processes), into the product structure and into the classical PLM configuration management, Fig. 3.

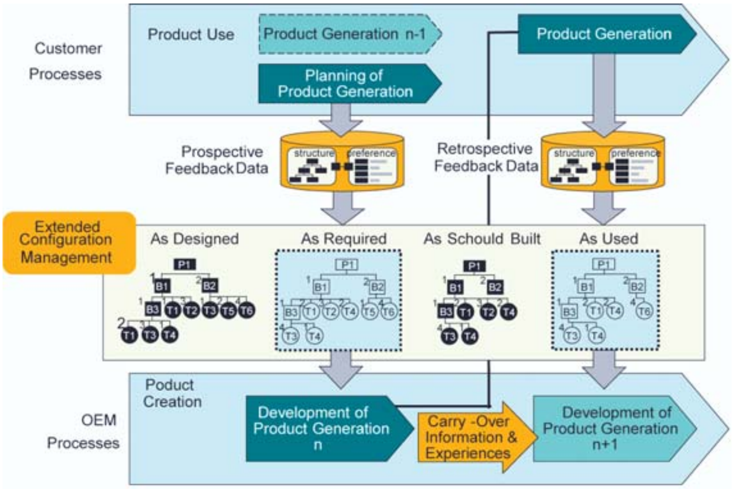

Fig. 3: Extension of the PLM approach for the management of customer feedback information

2.4 Covered Phases of the Product Lifecycle

The generic PLM models, methods and tools cover the whole product lifecycle. Specialised models and methods from existing PLM solutions are focused on the product development. Future specialised PLM models, methods and tools will better support the management of other downstream product life phases like

- planning and simulating the digital factory,
- technical sales including product configuration and the generation of online product catalogues,
- strategic product sourcing including the integration of external e-market places and online product catalogues,
- operation monitoring, optimisation and maintenance of the product during its usage,
- product recalls, take-back, recycling and disposal tasks,
- physical product tracking and tracing.

The extension of the PLM approach for the tracking and tracing of physical products is the goal of the research project “LAENDmarKS” carried out by ITM Bochum in cooperation with some IT and automotive companies [7].

2.5 Supported Process Types

Existing PLM solutions mainly support the management of value-added, core engineering processes. Future PLM methods and tools will also cover:

- the management of engineering support processes and
- product-related/strategic management processes

Future extended PLM modules for the assistance of engineering support processes include quality managemen t, product-related knowledge management, technical product documentation, product and process compliance checking with legislative constraints and regulations, as well as intellectual property rights (IPR) protection.

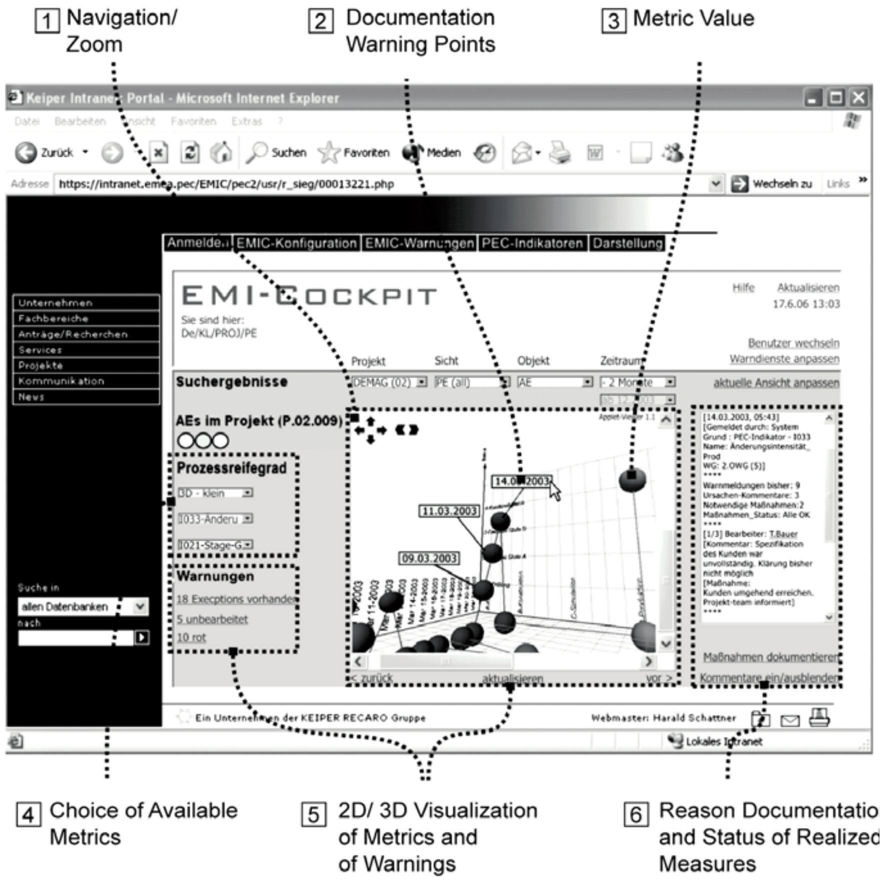

Fig. 4: Example for the visualisation and documentation of product and engineering process metrics within an extended PLM system

Another extension of PLM methods and tools will better support product-related management decisions. The extraction and filtering of product data from PDM systems will allow the visualisation of the current project or product status, reports showing the values of product or process metrics as well as historical analyses or forecasts. Fig. 4 shows an example of a PLM based Engineering Cockpit [8] realised by ITM Bochum. The software prototype is an extension of a classical PDM/PLM System. Future decision support methods and tools integrated in PLM will also cover the assessment of lifecycle costs, risks, energy or resources [3].

2.6 New Supported Product Types

Another expected evolution of PLM solutions will be the support of new product types. Existing PLM solutions are primarily focused on mechanical or electrical products. Future PLM methods will better support the integration of multi-disciplinary products (e. g. mechatronic products including micro-systems, process industry products). A special future PLM application will consider so-called "smart products" embedding information devices such as RFIDs or on-board computers. According to market analysts the majority of industrial products will be "smart" within the next decade. This means that each product will possess a unique identity and will track and trace all the product information over the whole lifecycle in real-time without an own power source. These embedded information devices in industrial products contain data processing and storing functions with a sensor reading capability and are able to gather signals from several sensors and to send them to an external environment. The availability of these product attached information devices will push the development of the PLM approach into the phases of the real product life as well as the integration of real and of virtual product lifecycles. The extension of PLM to "smart products" with a focus on the phases of production, product operation and product recall and recycling is followed by some research projects such as PROMISE [9] or LAENDmarKS [7].

Further product types that will be managed by future PLM solutions will be intangible products such as software or services. This service lifecycle management was addressed by some research projects [10].

The most complex future PLM approach will consider Product Service Systems (PSS) as a customer solution including networked physical products and product related services. Compared with static physical manufactured products, PSS's are characterised by complex and dynamic relationships between the physical components and the related services during the whole PSS lifecycle. The main goal of PSS is the optimal customer solution and customer satisfaction. PSS providers are responsible for the pro-duct optimisation during the whole product life. The management of PSS needs to consider the close relationship between the producers, the PSS providers and the customers. This new generation of Lifecycle Management (LCM) for PSS is being developed by ITM Bochum in the interdisciplinary Basic Research Center "Engineering of PSS" [11]. This long term research project is funded by the German Science Foundation (DFG) and is being carried out by the Ruhr University Bochum and the Technical University of Berlin. The new LCM approach developed by ITM Bochum includes new hybrid meta models for PSS and PSS lifecycles, methods for the support of dynamic PSS changes during the entire PSS-lifecycle, methods for the executive decision support and methods for the customer feedback management in order to optimise the PSS in real time during the PSS operation, Fig. 5.

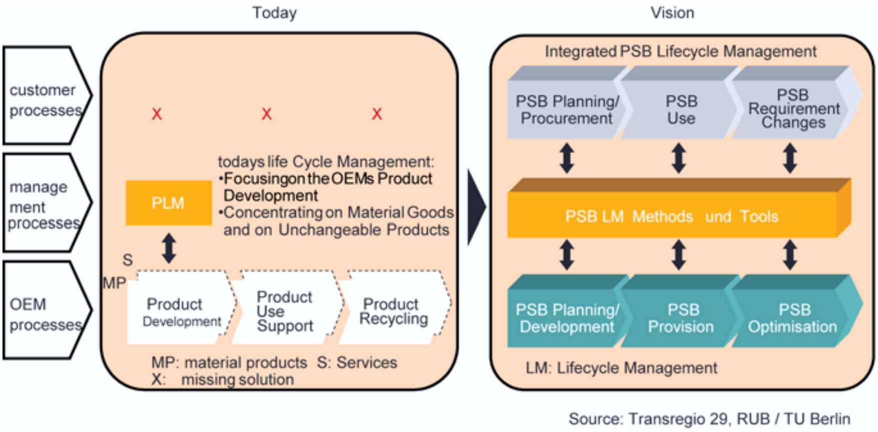

Fig. 5: Basic architecture of a new LCM system for Product Service Systems (PSS) as an integration platform between providers and customers

3 Conclusion

PLM has become the central management approach in engineering. The PLM vision is shared by the majority of PLM solution providers and users. Existing PLM solutions include mature methods and tools for the ma-nagement of product related data, engineering processes and integration of various applications. Due to the complexity of the PLM approach and the huge necessary customisation efforts, the penetration of PLM in the industry is still very poor. By using PLM, the most advanced PLM users in the automotive or aerospace industry have achieved a lot of quantitative and qualitative benefits and strengthened their competitive position. In the next decade the importance of PLM within the competitive strategy of industrial enterprises will grow and could gain similar importance to current ERP initiatives.

Unfortunately, in the past PLM approaches have mainly been driven by software providers and large user companies. The research on PLM is still at a very early stage. The shown on-going and future PLM research activities could bring a substantial contribution to more effective use and a larger dissemination of PLM in different industrial sectors.

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Modeling, Evaluation and Design of Product Quality under Disturbances throughout the Total Product Life Cycle

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Abstract

Comprehensive computer support for engineering activities in product design and manufacturing has been developed, and effectively used in industry for reducing product development lead time and enhancing total product quality. However due to rapid increase of product complexity, the product design process becomes very complicated, and technological errors in product development phases and subsequent product failures have now become a big issue. Current product modelling technology is not sufficient for coping with this issue because of the lack of accurate product behaviour prediction in practical environment. This paper surveys recent progress of virtual manufacturing, and clarifies various issues for product modelling. A new approach for product behaviour prediction under various disturbances is shown, and its applications for product quality evaluation and design are discussed.

Keywords

Product Modelling, Product Quality, Life Cycle Modelling, Product Behaviour, Virtual Manufacturing

1 Introduction

For new product design and manufacturing, a concept of digital engineering or virtual manufacturing has become very popular, and a variety of compute aided tools have been practically used in industry, such as CAD/CAM, engineering simulation, computer graphics, database/knowledge-base, process/work-flow management, product data management (PDM) and product life cycle management (PLM). Those methods and tools are now indispensable for competitive product development in a wide range of industry, such as automotive and electronics industry.

Current computer aided tools are very effective for reducing lead time to market, and cutting down required human resources and development cost. However they are still not very much effective to enhance product quality and reliability, and to predict and prevent potential product failure or safety problems. In this paper, current developments of computer aided technology for product developments are discussed, and future trends of technology developments are considered.

In recent years, due to strong demands from markets, industrial products, such as cars and electronic products, are becoming very complicated. Under the pressure of early market release, it becomes difficult to secure enough time and resources for verifying product quality, reliability and safety.

Most of such product quality problems are said to arise at the product design stage. Many product quality errors come from product design errors. There seem to be many reasons, such as:

- High complexity of recent products,
- Extremely short lead time for engineering,
- Incorporation of new technology,
- Unexpected usage by new customers,
- Environmental considerations, etc.

Current digital engineering methods and tools are not sufficient for coping with the above issues. Particularly capability of modelling products is very much limited. Digital mock-up technology is very popular, and has been widely used in industry. However those models can only represent product nominal information, and cannot deal with various disturbances arising in whole product life cycle, especially in product usage stages. Following modelling capability is lacking in current systems:

- Product behaviour simulation based on physical principles,
- Representation of various disturbances in real world,
- Unified model representation throughout the total product life cycle.

In the following sections, a concept of virtual manufacturing is briefly discussed, and requirements for modelling real world objects are considered. Then approaches to product modelling under disturbances and product quality evaluation methods are explained with several case studies. Finally requirements for the next generation modelling for product quality are discussed.

2 Virtual Manufacturing

A concept of virtual manufacturing has been well discussed [1, 2, 7], and practical systems have been implemented [8]. Here only characteristic features of virtual manufacturing are explained according to Fig.1.

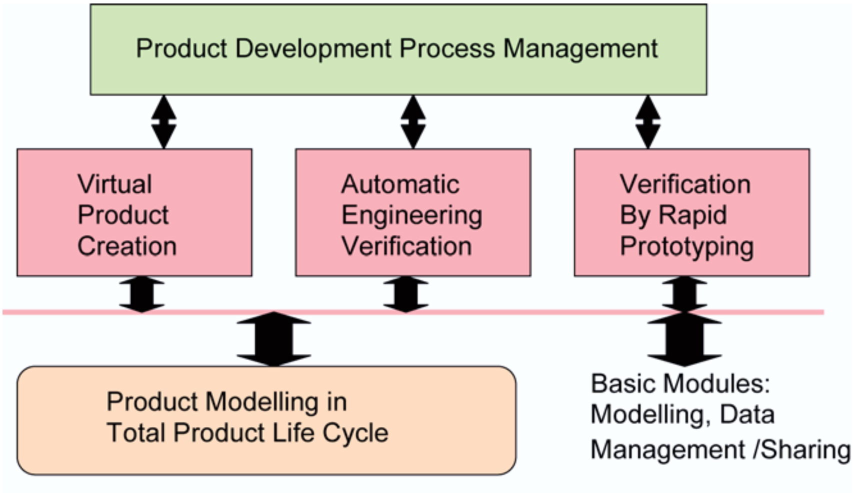

Fig. 1: Functional Architecture for Virtual Manufacturing

It is very important to characterize essential features of virtual manufacturing. New product creation heavily depends on human intelligence and interactions. For supporting able human engineers, interactive "Virtual Product Creation" module and comprehensive product modelling module are important. Once product information is designed, associated engineering verification for product functionality and manufacturing preparation shall be performed as automatic as possible by "Automatic Engineering Verification" module. If necessary, "Verification by physical Rapid Prototyping" is performed. System architecture should be as open as possible, so that any standard software can be plugged in the system.

3 Discrepancy between Modelling World and Reality

For coping with the product quality issue discussed in the Introduction, "Product Modelling in Total Product Life Cycle" in Fig. 1 is the most critical component in Virtual Manufacturing [3, 6, 10]. In current CAD/CAM and virtual manufacturing systems, product models can represent complicated product assembly and systems, but their capability is very much limited. Comprehensive simulation of product behaviour based on various engineering simulation methods is in principle possible. But it is not feasible in practice, because the problem size is too large for normal computational environment in design offices, and many model data are unknown and ambiguous.

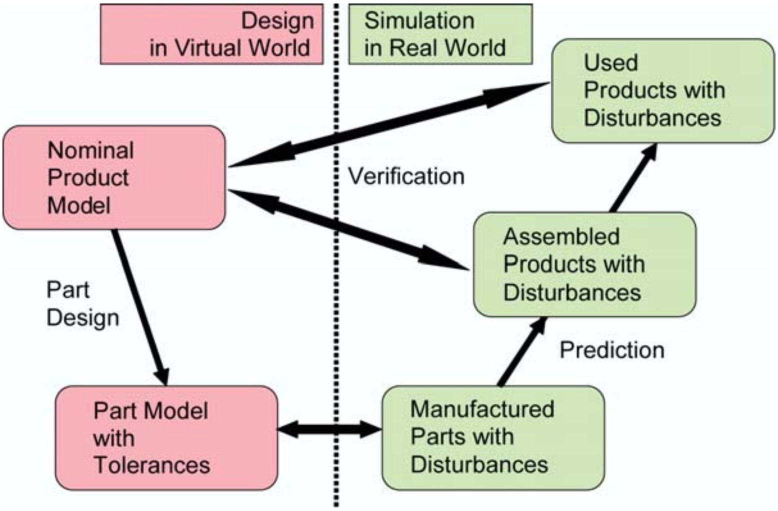

Fig. 2: Disturbances throughout the Total Product Life Cycle

As shown in Fig. 2, various kinds of disturbances exist in the total product life cycle, and they have very strong influences on product quality. Design philosophy and decision are required for achieving optimal life cycle product quality. For example, it is possible to reduce the influence of disturbances in product usage phase by introducing high-quality manufacturing processes, or by systematic maintenance in usage phase. It is effective for optimal life cycle design to predict the influences of various disturbances on product behaviour and quality. Here product quality is considered as a degree of discrepancy of product behaviour under disturbances from the nominal product behaviour without disturbances.

4 Product Modelling under Disturbances

For product quality evaluation, product behaviour is analysed under various kinds of disturbances introduced in Fig. 2. A general framework for product modelling with disturbances is shown in Fig. 3 [5, 9].

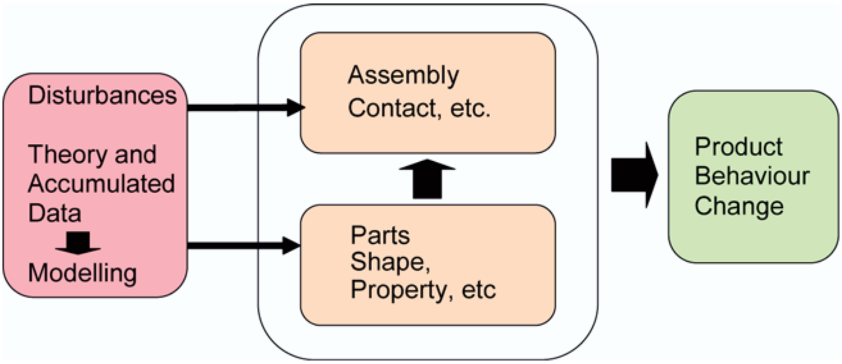

Fig. 3: Product Modelling with Disturbances

Many kinds of disturbances can be considered in product life cycle, such as forming and machining errors, assembly inaccuracy, material deterioration, wear, fatigue and corrosion in product usage phase. Most of those disturbances are difficult to formulate by theory. Experimental and accumulated data in practice are required to make models of practical feasibility. Models can be given in various formats, such as tabulated data, statistical approximations and computational procedures. Disturbance models are added to nominal product models which consist of assembly and parts information. For mechatronics products, multi-body dynamic analysis with rigid body and flexible objects is applied. According to the disturbance models, product model data are modified. For example, part shape is deformed, material property is changed, and contact conditions among parts are given by various functions. Commercially available engineering simulation software can be used by customization for inclusion of disturbances.

Several case studies have been performed for testing the feasibility of product modelling with disturbances. Fig. 4 shows an example of a simple paper feed mechanism. A sheet of paper is driven by a Roller A, and after free motion, a sheet is fixed on a specified position by a Roller B. It is easy to simulate a nominal behaviour of this mechanism. However it is very complicated to precisely predict paper movements under various disturbing conditions, such as wear, surface condition and positional change of rollers. Nonlinear finite element analysis is performed for an assembly of rollers and paper with a set of different disturbing conditions. By sensitivity analysis, some critical parameters for quality design are identified.

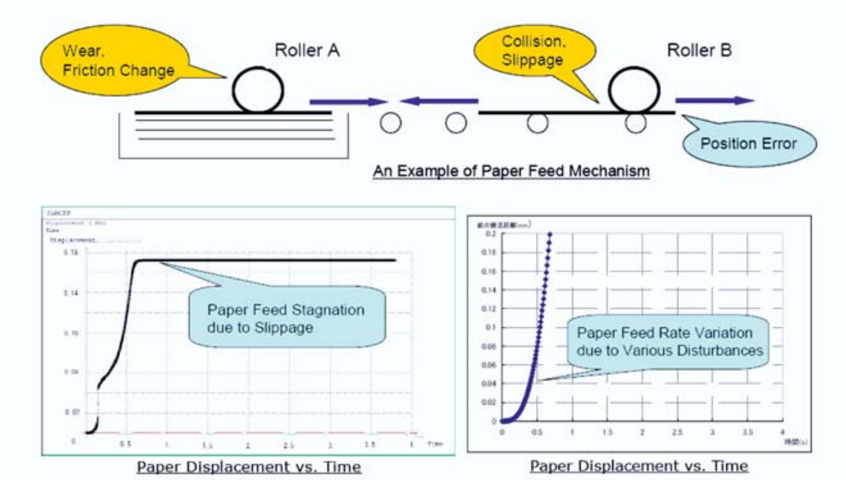

Fig. 4: Modelling of a Paper-Feed Mechanism under Disturbances

5 Evaluation and Design of Product Quality

For product quality evaluation, it is important to identify roles of product components for achieving product functions. Critical components for certain functions should be designed with care, and other components are carefully designed without excessive quality. Product components are called as features which collectively mean parts and assembly.

Additional information of product models is necessary for functional description. A general relationship among additional modelling information is shown in Figure 5. Left side of Figure 5 shows a modelling and analysis procedure for product behaviour under disturbances, as discussed in the previous section. Disturbances which may lead to possible product failure are accumulated in the Failure Mode Database. This process can be interpreted as a computer-supported FMEA (Failure Mode and Effect Analysis) [4].

Right side of this figure shows functional relations among features. Functional Relations among Features describe functional meaning among features. For example, some feature transfers certain force to a mating feature. Two features exist to support each other and to keep certain distance between them. Product designers should specify such information in parallel with product model creation as means to transmit their design intention to a design system. By applying a set of rules, a system can generate a Related

Feature Graph for Functions. This graph shows a list of related features for achieving a certain function. If products are complicated industrial products, it is very cumbersome and difficult to describe a list of related features by designers. To generate this list by computer support is very effective to reduce human effort and errors.

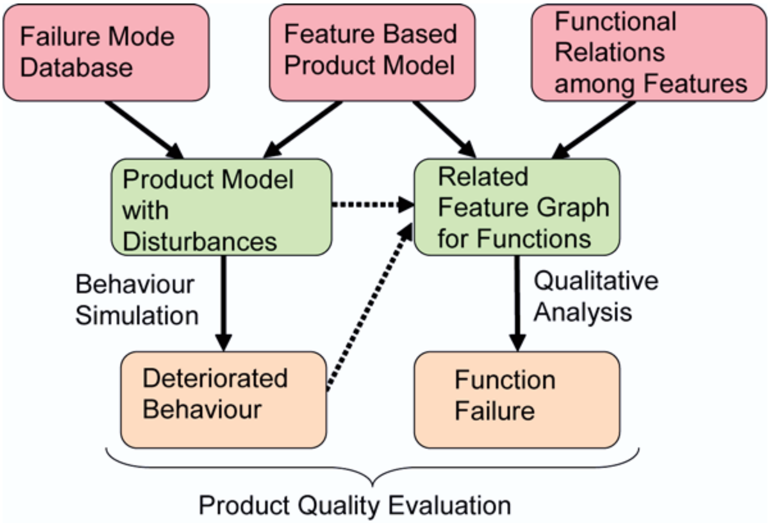

Fig. 5: Evaluation of Product Quality based on Failure Behaviour

Deteriorated behaviour analysis in the left side of Fig.5 performs a bottom up analysis of product behaviour. It enumerates any possible behaviour variations due to disturbances. But, it does not directly identify seriousness of such behaviour variations or product failure. Related feature analysis in the right side of Fig.5 performs a top-down analysis of product functionality. It identifies a set of related features for achieving a certain function. But, it does not directly show potential failure probability or criticality of related features. By comparing the both analysis, failure possibility, its criticality and associated features can be exhaustively examined. It is a basis for systematic product quality design.

Several case studies have been done for verifying the feasibility of the above approach. For illustrative purpose, a part of a related feature graph is shown in Fig. 6 in the case of a radio-controlled model car. Each box represents features, and functional relations are represented by arcs. Steering input from a top directed arc propagates to tyres. By assigning failure behaviour analysis results to corresponding features, product quality evaluation can be performed.

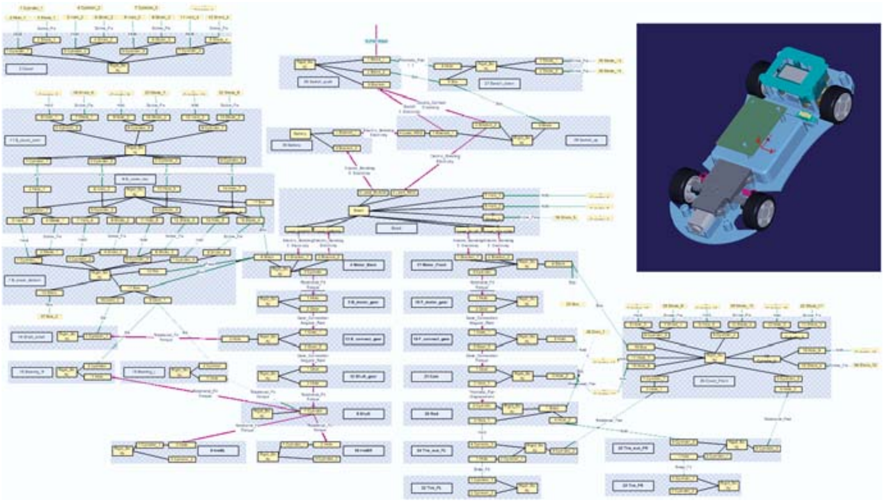

Fig. 6: Relationship between Product Functionality and Part Feature

6 Towards Product Modelling of the Next Generation

For supporting product design in the total product life cycle, particularly product creation process, current product modelling has many limitations. Current modelling scheme is very rigid for supporting a model evolution process from an initial conceptual product model to a detailed product model.

As shown in Fig. 7, model structure, properties and attribute values should be gradually elaborated in model evolution process. Flexibility in evolution process is very important, as represented by Least Commitment and Late Decision principles. Least Commitment means that required information only shall be determined. Late Decision means that decision shall be delayed as long as possible if enough information for decision is not available.

Based on a flexible model evolution process, a right quality product design becomes possible. At any stages of design processes, quality requirements can be exactly mapped to product information. Current modelling scheme is rigid, and trends to make over-commitment. This causes excessive quality or quality deficiency in later stages of product development.

A product model evolution process is very complicated, and specific to individual products. It is strongly required to capture such model evolution processes as a kind of modelling templates, and to reuse those templates for practical design activities. By such knowledge capturing based on product modelling, product quality design can be systematized as a routine design process.

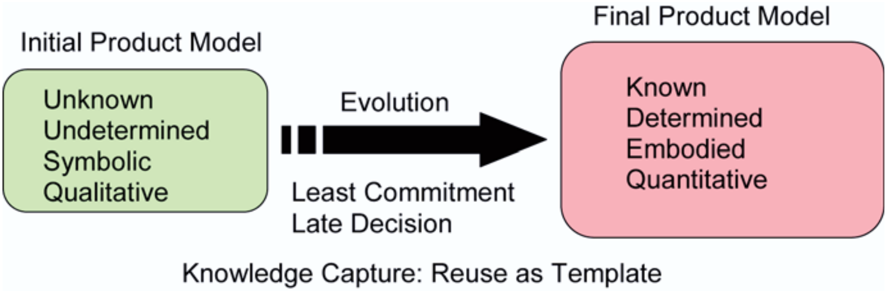

Fig. 7: Dynamic Evolution of a Product Model

7 Summary

Product quality is considered based on the discrepancy of product behaviour under various disturbances from product nominal behaviour. For systematic consideration of product quality design issues, a concept of product modeling with disturbances and functional feature analysis is proposed. Feasibility of the proposed concept is evaluated by several case studies. Further research and development work is necessary for comprehensive implementation of the proposed concept on top of current computer aided engineering systems.

8 Acknowledgements

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Hype or Reality: Service Oriented Architecture in Product Lifecycle Management – How IBM Can Help You Achieve Innovation That Matters

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Abstract
Products are becoming more complex due to rapid technical innovations, especially with the increase in electronics and software content even inside traditionally mechanical products. Furthermore, the design and supply chain of products have become more complex as well, with suppliers taking greater part in the design process of the overall system, often taking responsibility for the design and manufacturing of major subsystems. These challenges are causing manufacturing companies to rethink their business processes and systems for product lifecycle management.
We'll discuss how the current progress on enterprise application and infrastructure architecture based on service orientation (SOA) can enable the manufacturing companies to allow creation of highly integrated product lifecycle management processes, from the product concept to the product maintenance and retirement, while keeping the processes and the supporting systems flexible enough to easily adapt to changing business environments.

1 Executives are Searching for an Adge in an Increasingly Competitive Environment

Progress in information technology makes life more complex. The number of internet addresses will increase from 4.2 billion today to more than 35 trillion subnets supported by Internet Protocol 6, each of which could connect millions of devices. In 2006, the world produced more transistors than grains of rice. By 2010,supercomputers will execute one quadrillion calculations per second. And the world's codified information base is expected to double every 11 hours.The average car will have 100 million lines of code by 2010 – the Airbus A380 already contains more than a billion lines of code today.

In this quickly changing environment, CEOs of leading companies questioned during an IBM survey in 2006 see the ability to proactively manage change as a key success factor. 87% of CEOs believe change is needed to drive innovation,with the major drivers of change being intensified competition, escalating client expectations, technological advances, regulatory concerns, marketshifts, and globalization. To survive in an increasing competitive world,executives are looking for

- Business decision support and collaboration
- Flexibility and responsiveness
- Integration with the value chain.

Integration of new and existing systems is essential to them. Nearly 80 percent of CEOs rated business and technology integration of great importance. However, CEOs have a major "integration gap", where only half of them believe that they are executing satisfyingly. CEOs are embracing change by innovating. The top innovation priorieties are

- Business Innovation: Innovation in the structure and/or financial models of the business
- Product Innovation: Innovation applied to products or services or"go-to-market" activities
- Infrastructure and Operations: Innovation that improves effectiveness and efficiency of core processes and functions.

In manufacturing industries companies, fully leveraging product lifecycle management (PLM) concepts as a strategic initiative requires more than software. Key areas are

- Business Decision Support and Collaboration: Single view from which executives can collaborate and access the information with which to make business decisions
- Flexiblitity and Responsiveness: An infrastructure that can adapt to new business models and rapid business change
- Integration with the value chain: Integration with the rest of the value chain so that PLM is no longer just an "engineering" application, applying to product development, but a source of all product information, including pricing, market demand, portfolio costs, etc.

2 How can Product Lifecycle Management Evolve to Address Changes in the Business World

The scope and definition of PLM continues to expand and mature, see fig. 1.

Traditional State	Desired State
PLM: Software that Engineers Use to Design Products	PLM: Entire Lifecycle of Service and Product Creation, Use, Maintenance and Retirement
Driving Force: Cost Cutting and Worker Efficiency	Driving Force: New Customer Business Models in Conjunction with Gains on Efficiency and Productivity
Program/ Project/ Model Silos	PLM Requires Commonalty Across the Enterprise an „ Extra- Prise “
Heterogeneous System, Interoperable Data	Interoperable System through which Information Flows Freely and Securely
Innovation Managed with in an Enterprise	Innovation Generated along the Ecosystem Value Chain; more Innovation Expected from Supplier

Fig. 1: The scope and definition of PLM

A variety of value chain elements are interconnected with various functions and application domains, see fig. 2

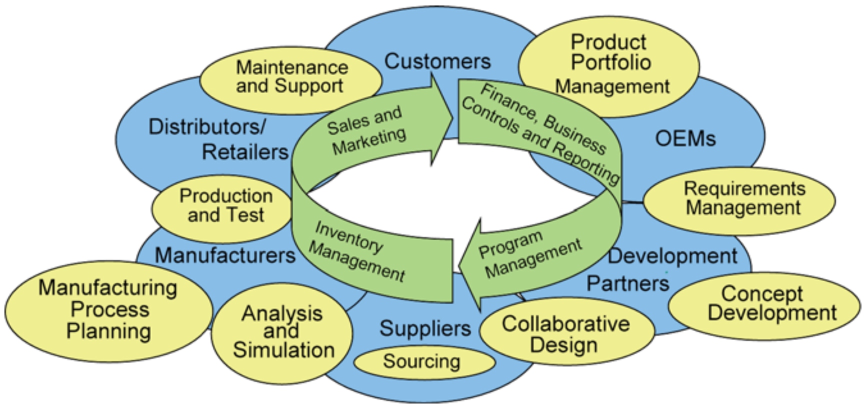

Fig. 2: Interconnection of value chain elements with various functions and application domains

3 Product Lifecycle Management and Service Oriented Architecture

Service Oriented Architecture is like building blocks. Building blocks represent reusable business services, such as “initiate program change” “request supplier quote”, “view related product info”. SOA allows you to modularly assemble and reassemble the blocks to suit your needs supported by business and role-specific processes. This makes it easier to integrate people, processes and information. Without service orientation, integrating existing systems and creating new services can be as tough as knocking down walls, as applications would end up having to be “ripped an replaced”. Even though the idea is not completely new, now is it time for service orientation:

- Necessary software to get started is available today
- Widespread adoption of open standards permit improved business flexibility
- Best practices for effective governance are available now
- There is increasing demands to keep pace with customer demands and the need for a customer centric organization

As Thomas Friedman stated in “The World is Flat”: “We are taking apart each task and sending it …. to whomever can do it best … and then we are reassembling the pieces”.

The current situation in many manufacturing companies around the world is reflected in Fig. 3.

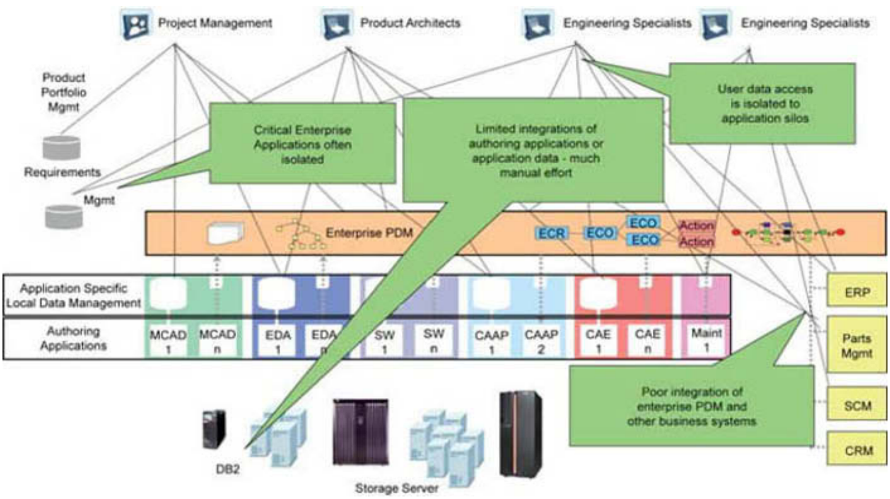

Fig. 3: The current situation in many manufacturing companies

This is multiplied by the increased complexity across supply chains/value networks, see Fig. 4.

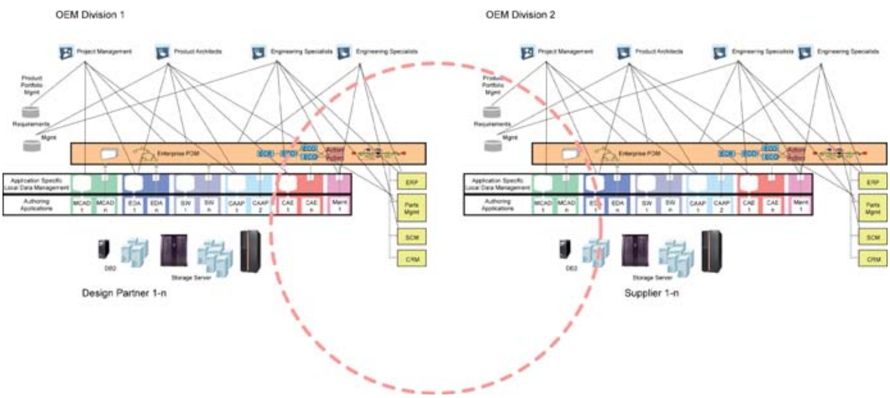

Fig. 4: Increased complexity across supply chains/value networks

A state-of-the-art, SOA based PLM environment provides the following components, see Fig. 5.

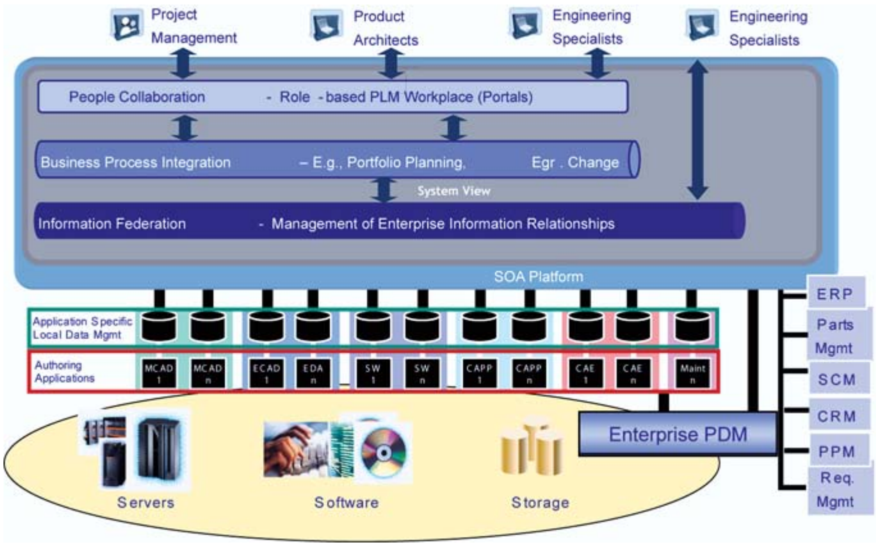

Fig. 5: The components of SOA based PLM environment

IBM's recently announced Product Development Integration Framework (PDIF) supports several specific product development solutions, see Fig. 6.

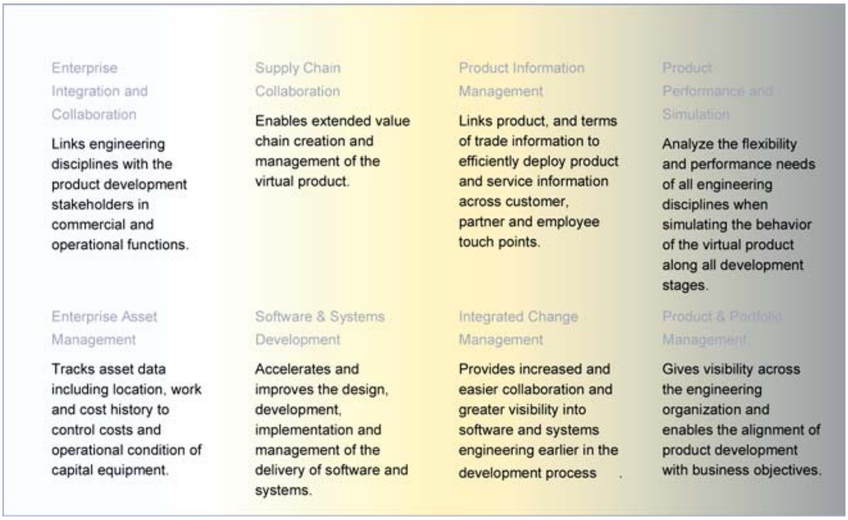

Fig. 6: Support of IBM's Product Development Integration Framework

Using these concepts, first pilot users achieved significant business results:

- Productivity gains of up to 20%
- Shortened order-to-delivery cycles
- Shortened design cycle time up to 30%
- Reduced IT expense of 5%
- Shortened simulations runs from 72 hours to 4 hours.

The Future of Product Development in India

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Abstract
A product is reflects the constraints, beliefs and aspirations of a society. Product development both influences and is influenced by the growth of a society and its economy. India is a fast growing economy. We use a brief historical, socio-economic account of India as a backdrop to detect the drivers and roadblocks to its economic and social growth. In this context, current and future trends of PD practice, education and research are sketched. *Products* are taken as artefacts of the act of designing, without limiting to only those created by industry in a market-economic context.

1 Introduction

India has 1.2 billion people, with 3.4% of the world's landmass but 16% of its population. The economy of India is the 3rd largest in the world as measured by PPP, and 10th largest if measured in USD exchange-rate terms [The Hindu, 2005]. It has the 2nd fastest growing major economy in the world, with a GDP growth of 8.9% in 2006–7. Due to huge population, its per capita income is $3,300 at PPP and $714 at nominal [17]. India has a highly multilingual, pluralist and tolerant society. It is the birthplace of 2 (Hinduism and Buddhism) of the world's 5 major religions, with 325 languages spoken of the world's 2820 [Ministry of Education. The quantum and quality of PD as practice both impacts and is impacted by that of education and research on PD. This paper analyses progress in India in these areas, and predicts their trends in the next decades.

2 Historical and Socio-Economic Background to Growth

Indian Civilisation has a (pre-) history of 12,000 years of development, starting from early settlements in Afganistan in 10000-8000 BC [1]. It subsequently grew into urbanized settlements within Indus-Saravati Valley civilization that flourished in 3000-1500 BC, developing into cities that practiced agriculture, used uniform weights and measures, made tools and weapons, and traded with other cities in India and abroad [11]. This was followed by growth of city States like Kashi, and large empires like the Mauryas and the Mughals, integrating much of Afghanistan, Pakistan and India till 1700 AD. In recent past, India had been a British colony (1757-1947). India always maintained trade links with other civilizations. It is the trade links with the Arabs that enabled Arabs to learn Indian numerals; these were later transmitted from Arabia to Europe that gave it its misnomer 'Arabic' numerals [6].

Before the British colonized India, it had one of the largest GDPs in the world. An estimate by Maddison [2001] puts India's share of the world income at 22.6% in 1700 AD, comparable to the whole of Europe's share of 23.3%. This fell to 3.8% in 1952. India followed a socialist-inspired approach for most of its independent history, with strict government control over private sector participation, foreign trade, and foreign direct investment (FDI). However, since the 1990s, it opened its markets through economic reforms by reducing government controls. The GDP has seen a corresponding progress. During the socialist-inspired phase, GDP growth was 3-3.5%, but gained momentum since the 1990s with a growth rate of 6%. Subsequent growth has been 6.0-8.5%. Growth in Indian economy is fuelled by 3 sectors: *agriculture*, *manufacturing* and *services*.

Agriculture and allied sectors accounted for 18.6% of the GDP in 2005 (from 50% in 1947), and employed 60% of the workforce [17]. As the largest employer of people, it is significant for India's socio-economic development. In spite of self-sufficiency in food production and steady growth in yields per capita, there is huge scope for improvement, in yields as well as growth, which is stagnant in this sector. *Manufacturing* sector has 27.6% of the GDP. It employs 17% of the workforce [17], growing at 10-11%. Economic reforms brought foreign competition, privatised some public sector industries, opened protected sectors and allowed consumer goods production to expand. Indian private sector, handled the competition by squeezing costs, revamping management, designing new products and relying on low labour costs and technology [16]. Indian industry is going global through acquisitions, and credit-worthiness of some is better than that of GM and

Ford. The *Services* sector employs 23% of the work force. It grew at 7.5% in 1990s from 4.5% till 1980. It has the largest GDP share, 53.8% in 2005 from 15% in 1950 [17]. IT industry accounts for 1% of its GDP or 1/50th of its services. Business services are growing the fastest: the no. of telephone lines grew from 5m (1990) to 140m (2006).

3 Major Drivers for Development

Gurcharan Das, former CEO of Proctor & Gamble India, sees as unique features of development in India, its primary *reliance on its domestic market*, focus on *consumption* rather than investment, on *services* more than on manufacturing, and on *high-tech* rather than low-skilled manufacturing [3]. China's growth is fuelled by improved infrastructure and foreign investment for selling low-priced goods to the West, while India's growth is due to increase in domestic productivity (30%) and consumption. Consumption accounts for 64% of India's GDP (58% for Europe, 55% for Japan, and 42% for China). This model provides better insulation of the economy from global fluctuations, and less inequality among people (measured by India's low Gini index of 33, against China's 45, USA's 41 and Brazil's 59). We see 6 major drivers for the Indian economy:

The *market size,* with the growing middle class with increasing purchasing power, is 300 million (similar to corresponding size in EU or USA). It grew from 10% of the population in 1980s to 25% in 2001 [2]. India is the only country where the *size of its working population* will grow in the next decades: 57.7% in 2001 to 64.3% in 2026 [15]. The 3rd major driver is *knowledge, entrepreneurial capability and confidence* of the leadership in the working population. The 1st stems from the Indian tradition of knowledge cultivation that led to major intellectual advances. However, knowledge in areas of abstract thinking, e.g., mathematics grew in communities different from those with knowledge of craft and engineering. The 2nd, entrepreneurial capability, is traditionally cultivated by yet another community. Growth in confidence is new, and probably due to the competitiveness of its IT and manufacturing industry.

Financial structure of the Indian economy is relatively sound. External debt to GDP ratio improved from 38.7% (1992) to 17.4% (2005). Inflation rate has been 4.39-5.6% in the last 5 years. FDI increased by US$20b in 15 years. Merchandise exports increased from US$52.7b (2002-3) to US$102.7b (2005-6); service exports doubled in the last 2 years. National savings increased from 26% to 28% in 1 year [5]. The 5th major driver is *awareness of* *the consumer and availability of information*. Authorities in India have been bureaucratic and non-transparent in providing information to people. While this trend continues, there is growing strength in the consumer and human rights forums, introduction of the Right to Information, and increasing use of the internet as a medium that is difficult to control. The 6th major driver is *open access and competition*, which gives an opportunity to all competitors, and invites development and use of cutting edge technologies and knowledge resource-effectively.

4 Major Roadblocks to Development

Eight major roadblocks to development of India are identified below. The 1st roadblock, *poverty,* is a serious problem. Although down from 36% people below poverty line (BPL) in 1994 to 25% in 2005, 260m Indians still live BPL. Sustained growth of 8% could double per capita income in 10 years, with substantial reduction in poverty. The 2nd roadblock is *poor health and sanitation support*. Infrastructure and personnel are inadequate, and AIDS threat to become an epidemic. India's health expenditure is US$99 per capita compared to China's US$261 [18].

The 3rd roadblock is the *lack of uniform and quality education* to the population, and inadequate research for knowledge creation. Literacy rose from 18.3% in 1951 to 64.8 % in 2001, but it is still poor at 65.38%. In rural India, 75% of schools have one teacher for many classes in a single classroom. Public expenditure on higher education is another indicator: while China spends $2798 per student, India spends $406. Poor infrastructure and teacher-salary are major reasons. Resulting impact on India's research? Its share (2%) of the total no. of research papers in the world is tiny if compared with that of USA (35%) or Germany (9%) [8].

A major reason behind many of these roadblocks is the existence of huge *corruption* at all levels. It takes the form of bribes, tax evasion, embezzlement, etc. Yet, India's corruption may be declining, as seen by its index on corruption moving from 2.8 in 2003 (0 being the most corrupt) to 2.9 in 2005 [7].

The 5th roadblock is *inadequacy of physical infrastructure and basic amenities*. Since 1950s, India allocated half of the total budget of its 5-year plans for infrastructural development. However, this was in the hands of the public sector, plagued by corruption, bureaucratic inefficiencies, urban-bias and investment non-scalability. India's low spending on power, water, construction, transportation, telecommunications and real estate, at 6% of the

GDP compared to China's 20%, is a major obstacle to its development.

The 6th roadblock is a *lack of adequate protection of knowledge capital*. The recognition of knowledge as property is recent in India, leading to plagiarism, both by foreign companies trying to steal traditional knowledge [14] and by Indian companies copying designs and products. Without effective measures against these, development will be costlier.

Environmental degradation in India is growing faster than its GDP. There is a steady increase in fossil carbon emissions in India (as in China and Brazil), which indicates increase in its pollution level. Since growth is typically proportional to energy consumption, this is to be expected. The other environmental threats come from rapid development in a country with no overall environmental protection policy. Environmental degradation will be fast, unless measures are taken to rein in pollution, including development/deployment of cleaner technologies, products and services.

Terrorism and insurgency are rising in India, in two types of conflict. The first is separatist movements, in Kashmir and North-eastern states, funded and fuelled by Pakistan. According to some estimates, 84,000 civilians lost their lives due to militancy in Jammu-Kashmir alone. The second is the 'people's war' groups', an extremist communist movement prevalent in regions under acute poverty, primarily as a reaction to the sharp difference in economic and social status of the poor, and the social apathy and corruption in reducing this. Terrorism is a major obstacle, damaging resources, and disrupting peace which is essential for growth in an economy.

5 Technology and Product and Development in India

Technology/product development in India is divided here into 3 phases: prehistory till independence, pre-liberalisation, and post-liberalisation.

From *prehistory* till independence, India developed indigenous technologies. The Indus-Sarasvati Civilization was the world's first to build planned towns with underground drainage and civil sanitation. Weights and scripts were standardized and used for millenia. Oven-baked bricks were invented in India in 4,000 BC. What some historians call the "Persian Wheel" is indigenous to India. Since ancient times, Greeks and Romans imported Indian textiles. The earliest industry relocated from India to Britain was textiles and was the first major success of the Industrial Revolution, with Britain replacing India as the world's leading textile exporter. However, the technology, designs and raw cotton were initially imported from India while India's indigenous textile mills were being outlawed by the British. In 1500 BC, Indian wootz steel was popular in Persia for making swords. Rust-free steel was an Indian invention. Delhi's iron pillar (402 AD) is a metallurgical marvel showing minimal signs of rust. The famous 'Damascus steel' swords were made from Indian steel imported by Europe. The Sheffield steel in the UK was Indian crucible steel. Shipbuilding was a major export industry in India, with Arab and Portuguese sailors as clients, until the British banned it [13].

The *pre-liberalisation* phase (1950-1980) followed development in a mixed economy. Areas were demarcated between public and private sectors. The former had guaranteed sale, and little incentive to make products efficient, deliver on time or within projected cost. Some mission areas (e.g., Nuclear) developed indigenous solutions of high quality (e.g., satellites), but with sub-optimal use of resources. Private sectors had no competition, and corruption was used to maintain monopoly. The industrial and services sector grew very slowly during this phase. While the regime gave industrial sector time to produce most items indigenously, little incentive existed for products to be resource-effective. However, some engineers of high competence, knowledge and leadership grew in the mission sectors.

During the *post-liberalization* phase (1990-2006), PD has been influenced by 4 factors: Removal of the license *Raj*, entry of external competitors, privatization of Public Sectors, and Telecom-IT revolution. While the first three helped open the market and forced Indian companies to be competitive, the last one provided the first tangible means, visibility and confidence for them to compete globally. The sector grew at 10-11%, culminating, e.g., in India's first indigenous car 'Indica', or combat aircraft 'LCA'. However, the sector's GDP share is still lower than in China, and scope for job creation through mass manufacturing. A trend among global enterprises is to set up R&D bases in India to support their innovation. This sector has catered the middle class with better products, with an increase in patent filings; its growth in the last decade has been the second fastest (365%) in the world. A related movement is grassroots innovation - locals solving problems with the help of trained designers [www.nifindia.org].

6 Current Drivers and Issues with PD in India

The current growth in Indian economy is fuelled by two sectors: manufacturing and services. PD is the engine of growth in both these sectors, and its practice should crucially impact growth. The factors which accounted for 50% of GDP growth in 50% of the OECD countries in the 1990s are: fostering firm creation and entrepreneurship; fostering innovation and technology diffusion; seizing ICT benefits; and enhancing/realising human capital. Half of these drivers indicate the importance of PD as crucial for growth [12]. From the story of development in general, and that of products and services in India, we learn the following lessons:

Availability of market is crucial for growth of PD, which in turn drives market growth. India has a growing, unsaturated, captive market of middle class. The growing trend of offshore PD outsourcing is another opportunity. Expanding manufacturing from its high-tech, high-skilled focus to low-skilled mass manufacturing will lend scope for a wider industrial revolution. India also has a huge dormant market in the other 2/3rds of its people, for products that meet their needs at their very low income levels.

Availability of people at the working age is crucial for PD. This is high in India and will be higher in the next decades. Since much of the world will see a significant drop in its workforce with greater need for products, Indian workforce should play a primary role in global PD. The 3rd need is a continuous supply of *professionals with knowledge, entrepreneurial ability and motivation to compete*. India traditionally nurtured these in separate communities, while PD needs their integration. The above could be ensured only with sustained, quality education at all levels, especially in design and entrepreneurship, which is sorely lacking. There is an issue with this. A product must fulfil technical, ergonomic and aesthetic needs. While design teaching in India has been synthesis-driven, focusing on the aesthetic and ergonomic, *economic fulfilment of technical needs remains outside its realms*. Technology education, in contrast, has been analysis-driven, teaching *existing technologies with little stress on synthetic thinking, design approaches and tools*. This bi-polarity must give way to a holistic design education with focus on all aspects of the product, a tenet on which the design programme at Indian Institute of Science is founded.

Most roadblocks to development seem to present *new opportunities* for PD. Infrastructure must improve for better growth; greater expenditure in this should create new PD opportunity. Health and safety is rapidly developing as a service, but opportunity exists for PD, especially for the 'bottom of the pyramid'. Education and environment should present new technology, product and service opportunities, impacting on poverty, corruption and insurgency. *Protection of knowledge* is essential for a suitable PD environment, especially under the threat faced by traditional knowledge. This is generally more harmful than copying of specific products, as it deprives a larger number of people of livelihood for whom choice is limited.

7 Future of PD Practice

The trends in future PD in India are the following. Specialized R&D sectors will thrive in high-tech areas, e.g., semiconductor industry growing from US$3.25b in 2006 to US$43b in 2015. Focus will extend from the consumerist, cost-sensitive middle class to its lower part and to the 'bottom' of the pyramid. Major growth sectors are aerospace, automobile, infrastructure, consumer electronics and health. Environment and safety will be major concerns, and drive PD as consumers demand more and stricter environmental protection laws are implemented.

Export of products and designing will continue to grow, if quality PD personnel can be created and nurtured or knowledge provided through partnerships. Work will shift from modelling, analysis or bread-and-butter designs cutting down cost to performance-led jobs creating IP. This will drive quality PD education, and see growth in partnerships between industry and academia, for market understanding to marry specialist knowledge. Growth in designer jobs in India will follow the global trend (9%), possibly at a faster rate due to its greater demand in a developing economy. A trend in public sectors will be increased conversion of (spin-off) technologies into products, creating opportunities for employing designers. Human capital is a major resource of India. The chaotic, tolerant, multicultural, multilingual, democratic, ambience of India will remain a favourable, distinguishing factor in shaping its innovation potential [4].

8 Future of Education and research in PD

Education and research in PD must improve at all levels, with these trends: There will be manifold increase in design education in India, as seen in the growth of its design education programmes from 2 (1960) to 15 (2006). Design education will be offered as undergraduate and postgraduate programmes, in many areas of specialisation such as automobile-, animation- or craft-design. Imparting skills for questioning, problem definition, strategising and implementation for innovation will be key differentiators for competitiveness, distinguishing leaders from rote developers. Training in holistic design thinking, creativity, collaboration, environment and entrepreneurship, integrating all stakeholder needs, will be needed. Programmes training and updating product developers and grassroots innovators with knowledge of design thinking, methodology and tools will also grow.

Related bodies for recognition and control of design practice, education and research will emerge as the design community grows, leading to design policies, councils, conferences, journals and funding programmes. A major obstacle in promoting PD education is the lack of mass awareness about design. While humans are naturally good synthesisers and problem solvers as are basic to design, these get suppressed during formal education promoting analytical thinking only. Programmes for mass awareness and education on design and PD should be as commonplace as Physics, promoting design thinking - a fundamental human activity - across disciplines at all levels of education, so as to nurture design thinking since childhood.

A major obstacle in promoting research in PD is the lack of awareness, of the intellectual content of research in design, among traditional scientists and engineers who control academic resources in India. Another is the fragmentation in design academia about its identity and intellectual challenges. However, demand for personnel for growth of this sector will drive demand for trained teachers and researchers, fuelling growth in design research. This is offered in 3 institutions only, with IISc pioneering the 1st PhD programme. Very few design teachers (>20) in India hold a PhD. The quality of teachers and education in general, and that in design in particular will critically depend on 3 factors: an internationally competitive pay scale to attract the best to join academia in India, an open competition in regard to recruitment of teachers in education institutions based on merit, and a higher investment in the academic infrastructure. Major research areas in design in India will be creativity, collaboration, knowledge and environment. India-specific research in human factors, culture and aesthetics will grow. Major advances will be in interfaces with emerging technologies, e.g., nano-technology. Applications will be both traditional, craft-based, small scale sectors and high-end aerospace, automobile and allied sectors.

9 Conclusions

This paper attempts to predict trends in PD in India in the context of its historical and socio-economic past and present. Major trends in practice are likely to be on extending focus from the middle class to the needs of the bottom of the pyramid, and to low-cost mass manufacturing for job creation. In education and research, focus will be on design thinking, creativity, collaboration, knowledge and environment. Collaboration across the globe will play a major role in shaping these, as will global laws for protection of knowledge and environment. Availability of uniform education and basic infrastructure would play a major role in this transformation.

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Virtual Product Development as an Engine for Innovation

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Abstract
Innovation is one of the most important phenomena for the further development of industry and the resulting effects on society. Over the last fifty years the speed of changes has gradually increased. To be able to participate in this world of fast changes, it is necessary to thoroughly think about the current methods of product development and its future issues. A number of research activities are illustrated to show important future directions of development.

Keywords
Virtual Product Development

1 Success through Innovation

Innovation is one of the most important phenomena for the further development of industry and the resulting effects on society. Over the last fifty years the speed of changes has gradually increased. To be able to participate in this world of fast changes, it is necessary to thoroughly think about the current methods of product development and its future issues.

Innovation is the result of a number of different processes. In all cases it cannot be decoupled from invention. Innovation is the successful implementation of an invention on the market. The initial idea can be generated by research, can come from an inventor, a supplier, can be a follow-up of customer demands, or may be a necessary reaction to new regulations. An invention describes the technical realisation of this conceptual idea. Finally, it will become an innovation after the proof of its market acceptance.

These processes have to be taken and put into context with the ongoing demands of current trends such as: global product development and production, keeping export leadership position, replacement of pure mechanical functionality of products by mechatronic solutions, and distributed development. Furthermore products alter to become more sophisticated, more individual and complex. On the other side partially products tends to be simply according to target group. Also a change concerning the ownership of products can be observed. For some products it is more interesting to buy the output of them than to own them, like parts instead of a machine tool. This integration of products and services requires new procedures in development of both to provide appropriate and aligned solutions depending on the underlying business model.

The further evolution will definitely depend on the view to innovation and the performed strategy. It was shown in the field of CAD/CAM that companies who did not see the need for 32bit computers lost the ability to sell the so called turn key systems. The storage tube was not replaced by new technologies by some market leader. Instead of this products in automotive industries, aerospace, and mobile phones are examples for successful innovations.

Unfortunately the important meaning of innovation is still not recognised by many companies. Most of the large companies are aware about its importance. But only exceptionally a specific role and process within the company is installed in order to promote innovation in a structured and controlled way. A recent study processed at IPK revealed that also SMEs know about the meaning of innovation, but do not actively pursue process approaches or install tools to enhance innovation.

2 Approaches for Innovation Support

2.1 Controlled Speed for Product Development

In the last decade numerous approaches have been investigated in order to realise shorter product development times. Shortened lead times and time to market are very often used expressions. The situation has changed. Depending on the effort it is possible to accelerate processes dramatically. The system speed can be above what can be handled by complex non deterministic processes. Systems can run in some cases in an automatic mode without the direct control of designers. There are the extremes of automatic and interactive design, Fig. 1.

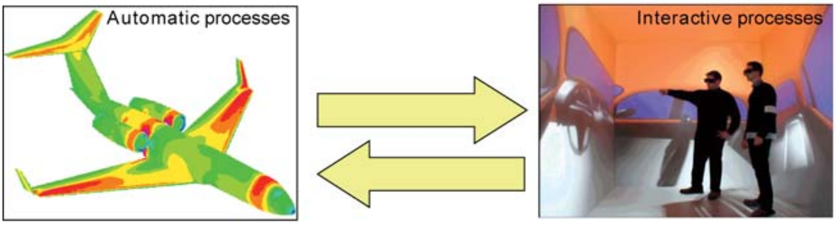

Fig. 1: Automatic vs. interactive processes

Taking a look back to the task of product development in the year 1850, the work was mainly done on the shop floor. This was an integrative approach, as it was performed by the foreman, who was responsible for the design and process planning of tasks. The work could be realised in a very close distance to the machines and the assembly places. To speed up tasks these could be performed with extra effort.

The benefits of integrative approaches were lost, when the rules of Taylor had been introduced for production. Comparing the current situation, there are similarities of to-day with 1850. After 150 years, a revival of integrative work with other means such as CSCW, Video-Conferencing, or Virtual Reality (VR) is applied.

The flexibility of controllable speed is supported by the capability to use integrated process chains based on PDM systems and to further intend Digital Master instead of only product models. The Digital Master comprises all relevant data which are certified for the mandatory usage in product and process questions. This is not yet state of the art at industry, but it can be seen that the solutions are coming closer, as the demand is expressed from more and more companies.

A new dimension of performance in product development will be available with the upcoming grid computing [1]. Although Moore's law will remain still valid in the coming years, it is important to see that grid computing can deliver an important contribution to increase computing power even on demand. This could mean that also SME's could have such computing power available for the enhancement of product development processes. The need for more computational power emerges from raised requirements for the representation of real world physics in computer internal representations. That makes it necessary to have larger amounts of data manageable and run more complex programs for simulation, evaluation and verification, Fig. 2. Grid computing cannot serve for real time purposes without delays. However it provides high performance services to companies which otherwise cannot afford these on a conventional basis. It will be a challenge, to develop this kind of services which can be also used by SMEs to make use of the capability of grid computing. The biggest challenges may be the close to real time performed visualization including modified VR-techniques.

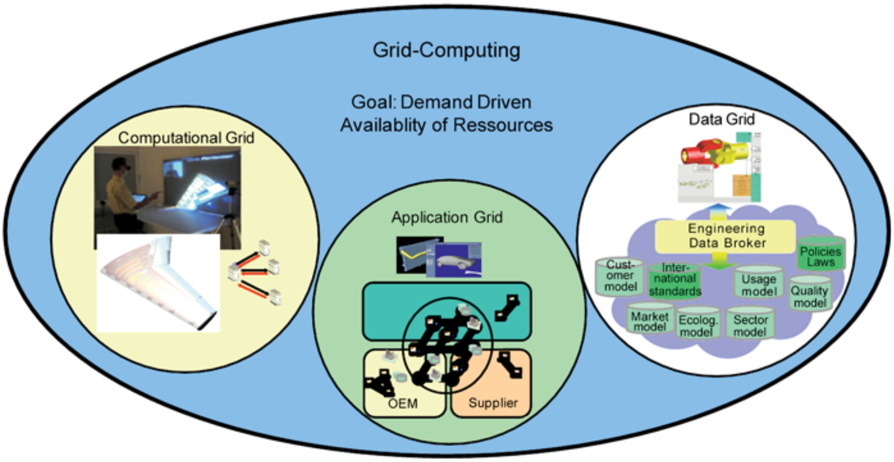

Fig. 2: Grid computing

To be able to adjust the product development speed to an objective schedule due to the competition or the customer needs, it is more and more necessary to further develop the ability of predetermining the product development time. Simple calculations have always been used, mathematical optimization tools are not really available due to the lack of sufficient process models. Therefore simulation seems to be an ultimate method. It can help to adjust to the needed development time, as by stochastic data the simulation is able to present a spectrum of probable times. By the possibility to select one of the probable times, the process parameters which have caused the result can be traced back. Therefore it becomes reality to make use of these data for controlling the process. Besides of this result, also cost estimates can be performed and the necessary number of feedbacks can be utilised to measure quality data, Fig. 3.

The application of object oriented Petri-nets is a proven concept for this simulation [2]. It cannot only be utilized for complex products in mechanics. Research work has shown the ability for using it for mechatronics products as well as for distributed product development processes.

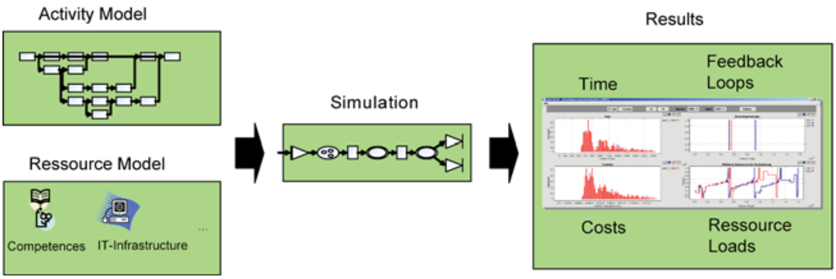

Fig. 3: Simulation of product development processes

There are a number of further questions related to the control of product development speed. What is an economically reasonable interval of product development times for a given product? How is it possible to adjust the product development with the needed product production and assembly time to come up with the demanded results? Is there a cost optimal solution, which gives time demands for the different sub processes? What about the time situation concerning the number of suppliers? Is there an optimum for this number? Will there be a method which makes the simulation of product development and the necessary project management compatible?

2.2 New System Functionality as a Driving Force for Innovation

It is not unusual, that designers are confronted to apply more than 15 different systems to fulfil their tasks. It can be doubted that it really makes sense, to come up with an even larger number of systems for providing more functions. The opposite is nevertheless true. The reason for more functionality is coming from the demand, to support the product development processes even in cases where it is not really possible to-day and nevertheless to ease the use of this system world. In the following, a number of research activities are illustrated to show important future directions of development.

The early phases of product development are often dominated by styling. This is a domain, which is inherently important due to the emotional effects on customers and the way of differentiation between brands. Styling in our days also has to be seen under the capabilities of manufacturing. As frontloading is a general demand for better, more effective product development, it is necessary to see also the usability of computer internal styling modules for the evaluation by physical simulation like CFD. A big benefit occurs if the same model can be used for simulation and for the first manufacturing steps, e.g. Rapid Prototyping. Another benefit arises from a styling model that can be generated in the computer with means which are accepted by the styling designer. The first steps into the direction of integrating a styling tool into the commercial CAD-world is promising, as NURBS surfaces can be generated, but are still not available in a sufficient quality. Subdivision technique has the potential but requires to be further developed to come closer to the goal [9].

The interaction of the styling designer with the model has to be based not only on the visualization of intermediate styling steps, but also needs to provide forces as if the styling designer would model on a real clay model. By this, the overall styling process accelerates significantly due to the cut down of process phases. Force feed-back is on its way, as first promising research results are there. It will take some more effort to be able to present an integrated process chain for these styling and design tasks. It could be thought of integrating as well converse engineering task.

Another system functionality is driven by the demand to support an integrated engineering and management of requirements during the whole development process. A direct coupling of requirements with product functions by using constraints aims to automate the further concretization like embodiment. This way of processing is of big interest for industry and leads to a number of advantages in adaptive and variant design [3].

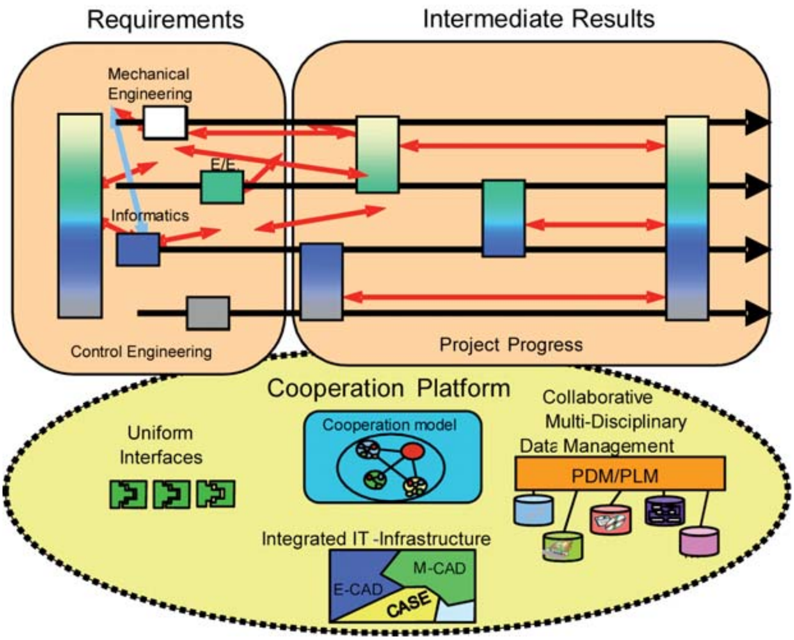

Fig. 4: Cooperation platform for mechatronics

Another challenge is to open the current system world support mechatronic engineering. In this case the requirements have to be distributed to mechanics, electronics and software. It seems that such a task only can be fully handled if a cooperation platform for mechatronics exists, Fig. 4, [6].

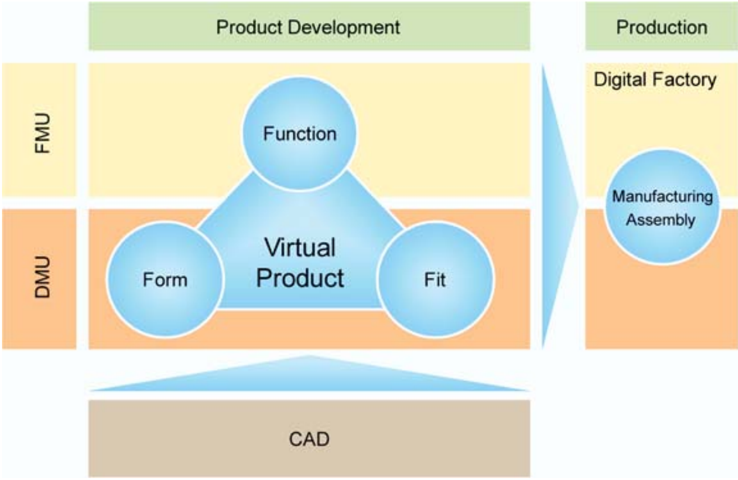

Fig. 5: Relations CAD, DMU, FMU, and Digital Factory

Another area of new functionality is the world of CAD, Digital Mock-Up (DMU), Functional Mock-Up (FMU), and the Digital Factory [4]. The relation between CAD and DMU is obvious, Fig. 5. A CAD-model is used and simplified in its shape representation for generating the DMU model. Thereby DMU functionality is focused to support visualisation and static analysis such as collisions predominantly. Actually only some simulations as kinematics and ergonomics are provided. Physical properties are not represented in DMU. Physical phenomena like heat transfer, electricity, vibrations, etc. are not investigable in DMU.

To apply DMU methods for the development of virtual prototypes, it should be possible to include functional property data into the DMU, which is by that turned into a FMU. FMUs will be able to be used to describe the functional and not only geometric behaviour of objects [5]. In the first steps this will be mechanical properties, but soon followed by everyone, what is necessary for mechatronics. It is very interesting to see, that the Digital Factory is already a domain specific FMU. The capabilities of simplified geometry are connected to factory functions like material flow and manufacturing processes.

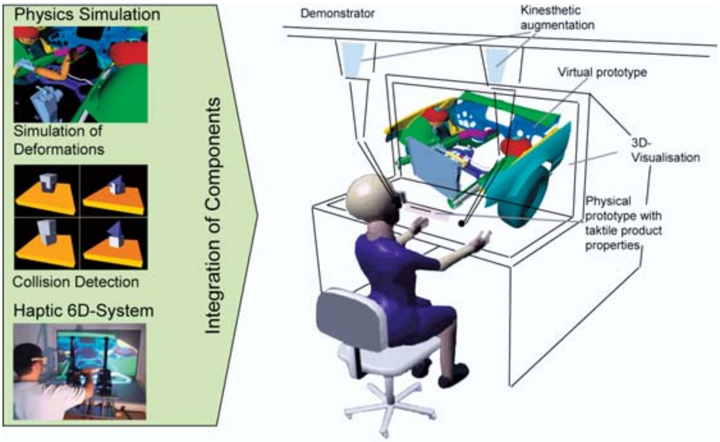

Fig. 6: Virtual Try-out & Training

Virtual and Augmented Reality are heading for new horizons in product development. Scalable presentations and stereoscopic viewing make the impression of VR-presentations realistic. The development of systems for interaction and feedback to the CAD-world show the potential of this field, which still needs research. But the required reality in VR is not yet reached. Also the combination with force feedback in kinaesthetic augmented systems will enhance the capabilities for example for Virtual Tryout, Fig. 6. In future it might not be necessary to have the high priced VR-Systems in use as a combination of VR and CAD may be available. The term VR-aided design is already used.

2.3 Computer Integrated Product Development Methods are a Basis for Process Innovation

Methodologies for design have been used since a very long time, unfortunately without the success which would have been necessary for industry. Nevertheless they have been used widely for educational purposes. Reasons for the less success than expected can be derived from the distance of some methods to practice. Especially the lack of customization potential is one of the obstacles.

Nowadays the usage of computers in product development is very common. In some cases the change from conventional design to computer support is performed in just copying conventional methods into the usage of software systems. This does not take into account the potentials of computerized systems at all.

The usability of computer integrated methods is very high. However, without computers they could not be applied. To name some: FEM, Knowledge Processing, DMU, VR, Fuzzy Logic and Neural Networks are all known very well for a while. The lack is their integration into a computer oriented design methodology. There would be even a chance of customization for the singular methods. As design methodology describes processes of product development, it should be generated a set of computer integrated methods. The important question is which is appropriate for a particular class of products. One demand should be mandatory: The designer should be able to select the methods according to his needs in respect to the product.

To go a step forward, it would be desirable, that the designer could make use of a system world, which is called "Case for CAD". As application systems on top of commercial basic CAD-systems generate a very high speed compared with the usage of the basic system only, there would be a big benefit to make such systems available for designers.

The idea would be to give the designer tools for describing the planned design process as well as the structure of the product he or she is working on. From this description requirements are derived which are used as search basis in a repository which might be a specific data base or even the World Wide Web. Assuming there would be a standard for subroutines, it would be possible to collect the needed functionality on the web. A system editor could help to generate the demanded software system out of this. It would be interfaced with the used basic CAD system. This means the designer could make use of tailor made application software that is even adapted to the current process status and also takes into account the maturity of the product model. Designers should not become programmers, but certain under standing for the capabilities and demand of software systems should become an essential part of their education.

Quite another success factor can be derived from further development of product models. As earlier described, product models are carriers of all relevant product data in the factory. Because of the more and more upcoming demand for the capability to do all steps of the product life in advance by virtual means, a new partial model becomes necessary [7]. This is the so called product condition model. It is a data collection over the life of a product. It gives information about the need for maintenance as well as repair. It can warn about upcoming situations and it can document. The product condition model is of help for the user but also for the developer. The developer can have access to the data of singular products or can get accumulated data as feedback from the field. This new method should become part of a computer integrated design methodology as soon as possible.

2.4 Key Technologies and their Amplifiers are Innovation Enablers

It is of strategic importance to analyze for two demands and capabilities. For this the method of roadmaps has been used since several years. For a company it should be mandatory to develop a roadmap concerning the own products every two to three years and to maintain that continuously. To find out about the further evolution of useful technologies for product development, it makes sense to perform road map studies in about the same time frame. In 2006, the Berliner Kreis performed a neutral roadmap study concerning the topics complexity, mechatronics and collaborative engineering and for 13 other topics with influence to product development [8]. The interesting results give strategic input to decisions to be made about methods and systems. The time span has been 10 years, but it is clear that the experience has to be repeated for getting guidance through the many available opportunities.

3 Conclusions

The ability to change is one of the most important issues for survival. It can be phrased that to innovate is a tool to change self-determined. Changing is often a creation of a crisis, but a planned crisis is always better than a crisis generated by the outside world, like the competitors. Innovation in processes and methods as well as in tools can support the innovation of products in a dramatic way. Business opportunities are no longer only dependent on time, quality and costs, but also on the ability to innovate. Innovation is one of the best tools in society to cope with the demands of sustainability as well as with the demands of employment. Not innovation by chance is therefore the goal, but planned innovation in product development. For this fundamental research and applied research are twin demands of the future.

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