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Building Innovation Pipelines through Computer-Aided Innovation

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- Open conferences;
- Working conferences.

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Preface

Nowadays, the term “innovation” has become a common mantra that is supposed to be the answer to several current issues. In industry, innovation is considered as the “key” to remaining competitive. In the scientific community, it is meant/seen/perceived as a focus/challenge to be addressed by all those disciplines that can contribute to the development of the collective knowledge in this broad area: from engineering to economics, from the physical sciences to the social sciences. Within the more specific domain of product development, a rich literature contributes to the discussion on the support provided by the innovation activities by means of dedicated methodologies and tools.

Nevertheless, computer support to innovation-oriented tasks mainly focuses on detail design and prototyping phases, while pioneer experiences relate to the earliest stage of the product cycle and to the information system supporting the innovation process.

Since 2004 the Computer-Aided Innovation (CAI) working group of IFIP (WG 5.4 of the Technical Committee dedicated to Information Technology Applications) has gathered academic scholars, industrial researchers and specialists interested in sharing their know-how on theoretical and practical aspects related to the development of computer-aided systems supporting the innovation process.

Being an emerging domain of science and due to its intrinsic multi-disciplinary nature, computer-aided innovation is broadly open to the contribution of interested researchers from basic research to industrial applications.

This book collects the accepted papers among those submitted to the 4th Working Conference on Computer-Aided Innovation, held in Strasbourg (France) from June 30 to July 1, 2011.

Some of them (N. Leon et al., C. Ramirez et al. H. Yu et al.) represent practical proofs of the benefits that CAI tools can bring, through case studies dedicated both to the inventive aspects of design and to the optimization of a conceptual solution. On the theoretical side, complementary aspects are covered, as a demonstration of the variety of issues that the research in the field of CAI has to deal with. S. Hüsig positions the development of CAI systems with respects to the more general trends of innovation, from designer-driven to user-driven, from closed to open-innovation. Bringing the focus on the market into the innovation process is also addressed by Q. Ma et al. through a discussion about how to structure flexible product platforms.

A key aspect covered by several authors is the relationship between innovation and the complexity of modern technical systems. C. Conrardy et al. investigate the possibility of automatically extracting a hierarchy of design conflicts, or more precisely contradictions, the elementary models of inventive problems according to the TRIZ theory. G. Syal et al. propose a methodology for the management of multi-physics simulations by networking CAE systems in order to support the development of complex products as in the automotive sector. H. Liu et al. describe an approach to the functional decomposition of complex system, which leverages TRIZ principles.

Among the other topics, F. Wuttke and colleagues address the uncertainty of innovation processes and propose an approach to support decision making, with a special focus on the automotive industry.

The fundamental characteristics that a computer-aided inventive problem-solving tool should have are discussed in the first part of the paper by Borgianni et al., while the second part proposes an algorithm for coaching the analysis of an inventive situation that the authors claim is suitable also for training purposes.

The assessment of the performance of R&D inventive activities is dealt with in the paper by L. Burki et al. also in the framework of the CEN TC 389 project, an initiative of the European Community aimed at establishing a norm to guide innovation practices in industry.

Last, but clearly not least, D. Russo presents a proposal to integrate eco-design principles and computer-supported analyses for reducing the environmental footprint of new products. Although several examples presented in this book deal with traditional industrial topics, such as those related to the automotive sector, not surprisingly sustainability, environmental issues and renewable energy sources seem to be a transversal topic addressed by several papers, since it is evident that a major thread of inventive problems that engineers and designers will have to cope with is making innovative products sustainable.

March 2011

Gaetano Cascini
Denis Cavallucci
Roland de Guio

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4th IFIP Working Conference on Computer-Aided Innovation (WCCAI 2011)

WCCAI 2011 was organized by

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A Sustainable Model of Function Decomposition Based on Effect

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Abstract. Function decomposition is an important step in the process of product design, in both original design and redesign. Following "Three-Flows Principle" complies with objective rules, and the result of product design proves its importance. For the many-to-many relationship between function and effect, when different effect is selected for a function, flows will be very different. The sustainability of product has close relation with the functions, principles, structure and material of product. In the process of function decomposition, designer should follow the sustainable design criteria for effects. Besides, it is significant to unearth available resources in function decomposition. A model of functional decomposition based on effect followed the sustainable design criteria and "Three-Flows Principle" is established in this article. Last, functional structure of heating equipment is established following both the new model and existing model. The results prove the superiority of the new model.

Keywords: function decomposition, effect, sustainability, available resources.

1 Introduction

Currently, the descriptions of functional structure are function tree and functional chain. There are many methods to establish function tree and two have good effect among them. One is a top-down approach, Function Analysis System Technique method [1]. Following this method, the function tree is depended on the experience of the designer. Another is a bottom-up approach, the Subtract and Operate Procedure [2]. The underlying assumption to use this method is that either a form concept or actual product exists. So it limits the chance to use it. The description of functional structure with the integration of function tree and functional chain is based on the operation analysis of flows. Flows are physical phenomena, which are, material, energy, and signal, intrinsic to the product function. So following "Three-Flows Principle" complies with objective rules, and the result of product design proves its importance. But, the results of patent analysis in TRIZ prove the many-to-many relationship between function and effect [3]. When different effect is selected for a

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* 1982-, master degree candidate. His research interests: innovative design.

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function, the flows will be very different. So the functional structure will be very experiential, without selecting the effect in the process based on "Three-Flows Principle". Secondly, the sustainability of product has close relation with the functions, principles, structure and material of product [4]. Moreover, it is difficult to improve the efficiency of the selected principle through subsequent selection of functions, structure and material.

The overall function is realized by a group of sub-functions organized with some relations. Sub-functions and relations constitute the functional structure, which not only describes the movement of flows, but also shows the relations between sub-functions. For convenient exchange, drawing functional structure should follow standard signs. The standard signs see Fig.1.

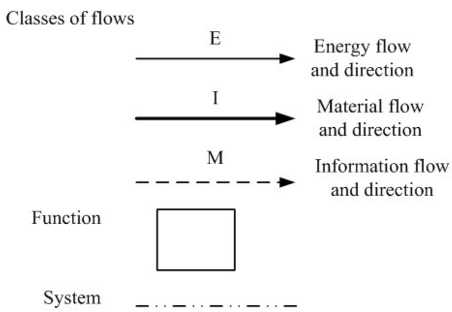

Fig. 1. Signs for functional structure

2 Function Decomposition

The purpose of function decomposition is to describe product on functional level. It will be significant to build a library of available resources [5] before function decomposition. An important aspect is the compare between input flows and available resources to seek the transition route. Moreover, along with the process of functional decomposition the library increases, because more effects will be selected and more output flows are available resources or will be transformed into available resources. More adequately available resources are unearthed, that should follow first material object then virtual object, more innovativeness the product has.

There may be some restraint between sub-functions, which are not resolved in the analysis process based on flows. So it is necessary to optimize the functional structure, mainly following sustainable design criteria for effect and function, between which there may be contradictions which should be resolved under the help of the contradiction solving matrix or separation principles from TRIZ [6].

Designer can plan product's layout in physical structure, through the modularization of functional structure. The modularization should follow some principles:

1. Divide a group of sequential operating functions for a flow in a module as far as possible.
2. Divide the functions in a module which has high dependency.
3. Ensure the convenience of module in manufacture.

3 Sustainable Design Criteria

The analyses of patents confirm the many-to-many relationship between function and effect.

In the one hand, different scientific principle has different flows, which's attribute determines the sustainability of effect. In the process of function decomposition, analyses of inputs and out puts are necessary, then add operation to ensure inputs can be got from available resources and outputs can be changed into available resources and with sustainability.

On the other hand, effects can be classified into produce energy, store energy, transform energy and utilize energy. In different effects the utilization ratio or transformation efficiency or production efficiency may be different. Furthermore, it is difficult to improve the efficiency of final products through subsequent selection of function, structure and material, if the energy efficiency of scientific principle selected is bad. So it is chiefly work to select sustainable effect for enhancing the sustainability of product.

In the process of function decomposition, selecting effects should follow the principles:

1. Try to choose principles with high energy efficiency.
2. Try to choose principles that need simple structure.
3. Avoid using the principle of electromagnetic radiation generated.
4. Avoid using the principle of environmental pollution produced.
5. Avoid using the principle of using or producing toxic substances.
6. Avoid using the principle of produces high risk of fire or explosion.

When combine functional structure, should follow some principles:

1. Functional structure should be as simple as possible. Less sub-functions as far as possible, in order to reduce the number of components.
2. Merge compatible functions.
3. Functional sharing principle, and avoid too complex components.
4. Multi-function principle, make the products and components with multiple functions.
5. Functional independent principle, allowing users to shutdown system partially or totally.
6. Avoid the functions that produce harmful material flows, add auxiliary functions to eliminate harmful material flows or change them into useful resources.

4 Sustainable Model of Function Decomposition

Fig. 2 is a process model of functional decomposition, following the “Three-Flows Principle” and sustainable design criteria. And in the Fig. 2, F (E) is the relationship between function and effect. The application process of this model is divided into nine steps: establish a library of available resources, decompose the overall function into primary functions, seek and select effects, analyze output flows, add operations, analyze input flows, describe functional structure, optimize functional structure and modularize functional structure. Some steps are repeated in the process.

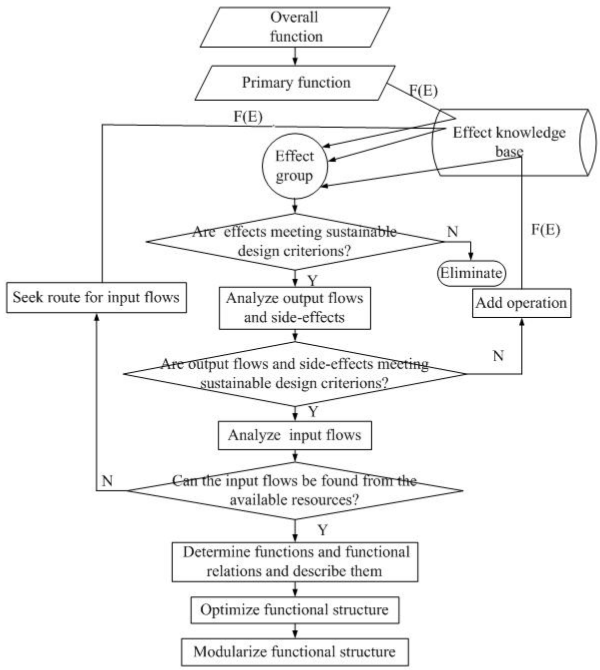

Fig. 2. Model of functional decomposition

5 Engineering Examples

The existing heating method is discontinuous, the efficiency of which is bad. Furthermore the heating is in settling chamber which restricts the continuity. In order to continuously deposit CdTe, it is need to separate heating substrate from depositing CdTe. The function of continuous heating equipment of the production line of CdTe thin film solar cell is continuously heating the FTO conducting glass to the required temperature in vacuum environment before the settling chamber.

The functional structure of existing model is established and is divided into several modules, as shown in Fig. 3. Fig. 4 is the functional structure of new model, which has considered the sustainability of the product and resolved the contradictions by TRIZ theory.

Functional design of continuous heating equipment confirms that the function decomposition based on existing module can search for functional structure according to technological and performance requirements, cost and simple structure only, while in the function decomposition based on the new module, designer not only according to technological and performance requirements, but also can directively select effect and analyze the sustainability of flows. So designer can consider the sustainability on the level of function and scientific principle.

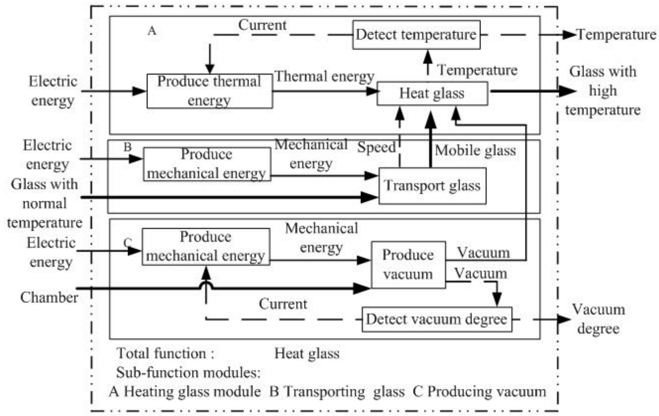

Fig. 3. Functional structure of existing model

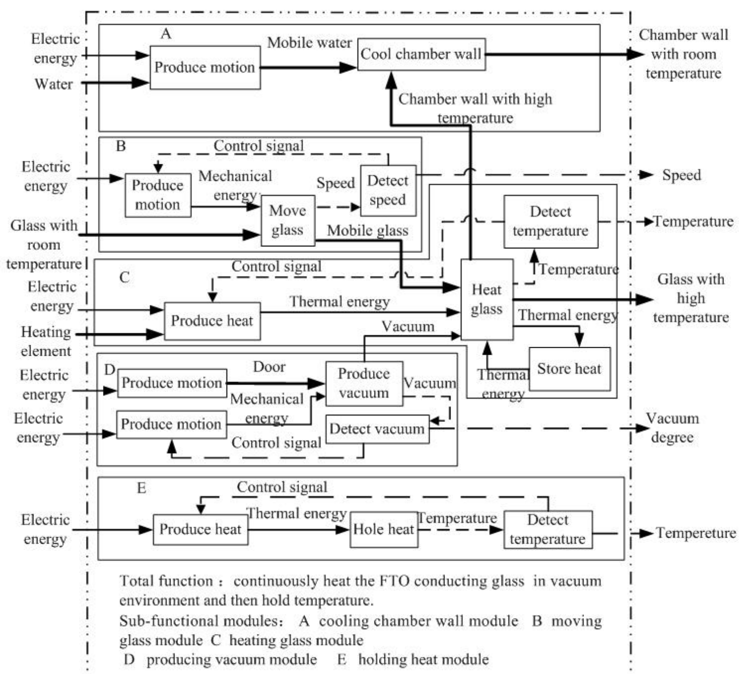

Fig. 4. Functional structure of new model

6 Conclusion

Designing sustainable product is the core of producing sustainable product and the crux of sustainable development of business. In the article, puts forward sustainable design criteria for function and effect and a model of functional decomposition. In the process of function decomposition, following the sustainable design criteria can realize the purpose that considering sustainability in parallel.

Functional design of continuous heating equipment confirms that considering sustainability in process of product design in parallel, can significantly improve its sustainability.

Acknowledgments

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Flexible Product Platform Based on Design Parameters

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Abstract. In the times of mass customization mode, enterprises face more changeable market demand. The traditional product platform can not meet the needs of all customer, therefore the flexible product platform is particularly important. But the method of parametric design is needed to make product platform to be changed rapidly based on flexible product platform. This paper connects parametric design and flexible product platform , and a design process based on flexible product platform with parametric design is developed. Finally the process is applied to the design of belt conveyor, and the flexible product platform with parametric design is set up.

Keywords: flexible product platform, parameterized Mass Customization, belt conveyor.

1 Introduction

The customers' demand for the product is continuously improving with the generation and development of mass customization. Diversified needs form customer leads to a large number of uncertainties, so in order to meet customer's different customization requirements enterprises have carried on variant design on the basis of the original product. In general, much business depend on common product platform to design new product, but the continuous improvement of complexity results in a large number of parts and components should be repeated designed in deformation design , this can reduce efficiency, increase costs and complexity of the production process. The current design method for platform placed more emphasis on the common structure of products share. However, the shared degree is inversely proportional to the market segmentation scope; this resulted in the contradiction between the generality and flexibility of platform structure. Only by understanding these uncertainties fully and reducing their negative impact, can enterprises develop a product platform with high-efficiency and high-quality.

So, this paper introduces a design method of flexible product platform for the products which have the same function. We should take into account some uncertainty in the future development of product when we begin to design a product platform, at the same time, add the parameterized design method to the design of product platform, finally a Parameterized flexible product platform is built which is based on these factors above. It can help the enterprise produce many kinds of

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variable products using the same product platform to meet customers' individual requirements on performance, appearance, size add so on. This can extend the life of product platform, reduce costs and improve efficiency.

2 Design Processes of Flexible Product Platform Based on Parameters

First introduce and study the related Concepts:

A product platform is the common technological base from which a product family is derived through modification and instantiation of the product platform to target specific market niches.

Parametric Design is for the parts or components, whose shape is case-hardened relatively; we can use a set of parameters to constrain the structure size and topology of the model. The parameters have an explicit correspondence with the controlled size of design object. A typical model can be driven when given it different sequence values of parameters to get the part model which meet requirements of the designer, this can meet the different needs of working performance by changing local structural forms and parameters of existing products.

Flexibility is desirable when a system of any kind is faced with exogenous uncertainty, but must be implemented carefully to minimize undesirable side effects.

2.1 The Research for Design Methods of Product Platform

According to the different ways to achieve the product characteristics in the product family, the design of current product platform can be divided into two parts: the design of product platform based on modular and the design of product platform based on adjustable variables [1].

The design method of product platform based on modular is mainly aimed at the product variants with different functions, it could derive products which meet different subdivided markets by adding, removing, replacing, modifying one or more modules in the platform. The main steps are: draw the product's features flow diagram at first, and then use the principle of third-rate to mark off the function modules of product, finally, get a modularized product platform through correlation analysis or modularity matrix.

The design method of product platform based on adjustable variables is mainly applied to products which have the same functions; it can achieve a series of product family by changing some features. The representative method is Product Platform Concept Exploration Method, (PPCEM) proposed by Simpson [2]. The method determines the appropriate scale factor by dividing the market grid, and then extended product platform in order to achieve the parametric design of product platform and personality structure.

The two methods mentioned above are main methods to achieve the design of product family based on the product platform. They have their own advantages, but have their own scope of application. Design using flexible product platform combines the advantages of both methods. The flexible product platform can be defined as an organization or system that consists of public and flexible elements (component, process or interface), we can achieve a range of product variants and product family by adjusting the value of flexible elements dynamically without changing common elements. When designing a flexible product platform, we should find the public modules of a series of variable products by marking off all modules of products at first, then determine the flexible structure of products by extracting the main design parameters and mapping to the physical structure according to the market analysis. Finally adjusting the main attribute parameter of flexible modules dynamically could achieve the products which meet the different market segments [3].

The following Figure 1 shows the outline and framework of the design process of flexible product platform brought forward by Suh [4].

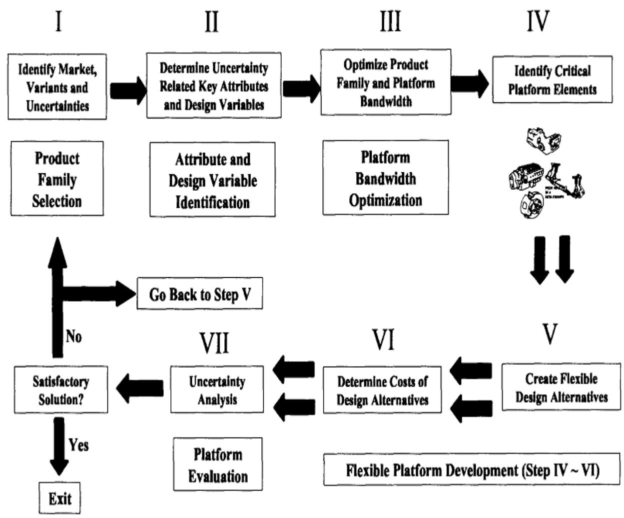

Fig. 1. Design process of flexible product platform brought forward by Suh

2.2 Design Method for Parametric Flexible Product Platform

According to the design process of flexible product platform, adding the variant design and parameterization, we can get a design method of flexible product platform based on parameter [5].The step are as following.

Step 1: Demarcate Market segments

Mark out the market segments, and constitute market segmentation grid.

In order to survive, enterprises must find markets, and then, define and segment them. Figure 2 shows a conceptual framework of a market segment, the entire market is divided into a number of market segments along horizontal and vertical. Each horizontal segment represents consumers of some products, while the vertical segment is divided into three grades, they are high-end, mid and low-end. Through dividing horizontal and vertical grid, a large market was divided into a number of market units.

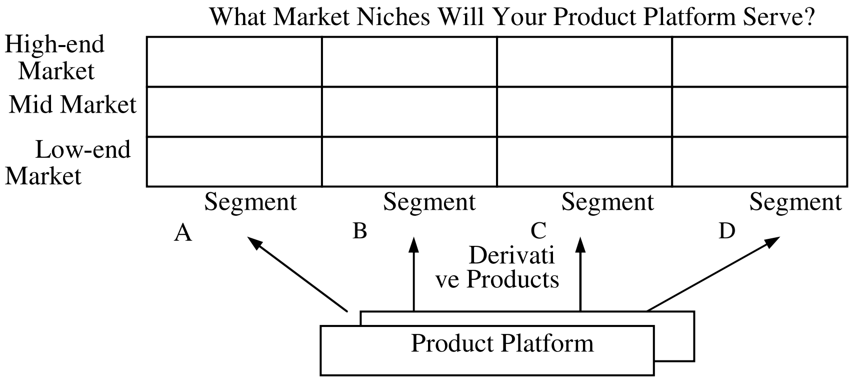

Fig. 2. Conceptional frame of market segmentation

During segmenting market and formulating the optimal platform strategy, designers need to identify the following variables:

Market segments of product: M={M1,M2,…,Mi}

Product variants: P={P1,P2,…,Pj}

Step 2: Analysis of uncertainty, determine the main parameters which affect performance, and identify uncertainties

Now we first introduce the method of DFV [5] .

There are two objects to use this method. One is to develop a method about structure designing. It is useful to help development teams to design a platform architecture which robust to future changing. The other is to define a measure of coupling between components. This measure includes the physical interactions between the components and indicates how likely one component affects another.

There are two indexes, Generational Variety Index (GVI) and Concept Index (CI). The generational variety index is an indicator of how likely the components of a design are to change over the life of the product platform. The concept index is a measure of how tightly coupled the design is.

The design steps for DFV method are as follows:

(1) Generate GVI and CI for the design.

(2) Order the components based on GVI.

(3) Determine where to focus effort.

It is a very important step to identify the uncertainty of product development in the future in programming a flexible product platform, because the position and using method of flexibility on the product platform depend on the uncertainty in future development .

Uncertainty can be divided into knowable-uncertainty and unknowable uncertainty. Knowable uncertainty can be got approximate solution using past experience and data or to be predicted by collecting experts' advice and the motive of consumes. Unknowable uncertainty could be found by using DFV.

Step 3: Optimization uncertainty, determine the range of uncertainty to get the bandwidth of platform, then optimization the product family.

During designing a product family, Simpson put the scale factor into robust design, as shown in Figure 3. Scale factor is a factor around which a product platform can be "scaled" or "stretched" to realize derivative products within a product family.

Correspondingly, two types of scale factors can be identified—parametric and conceptual/configurational related to the type of scaling. The relationship between each type of scale factor and the three types of leveraging are as follows:

Vertical leveraging: parametric scale factors, such as the length of a motor to provide varying torque or the number of compressor stages in an aircraft engine as in the Rolls Royce RTM322 engine example.

Horizontal leveraging: conceptual/configurational scale factors, such as the size of evaporator in a family of air conditioners or the number of passengers carried by the Boeing 747 family of aircraft.

Beachhea dapproach: combination of parametric, conceptual, and/or configurational scale factors as needed.

Scale factor may be discrete or continuous, however, only a lot of research is a continuous. Describe each one of the factors used a range of appropriate. Other, determine the ranges are also a part of the design process. Determine the range of the known parameters, design parameters and system constraints parameters, as well as the calculation formula, equation and so on.

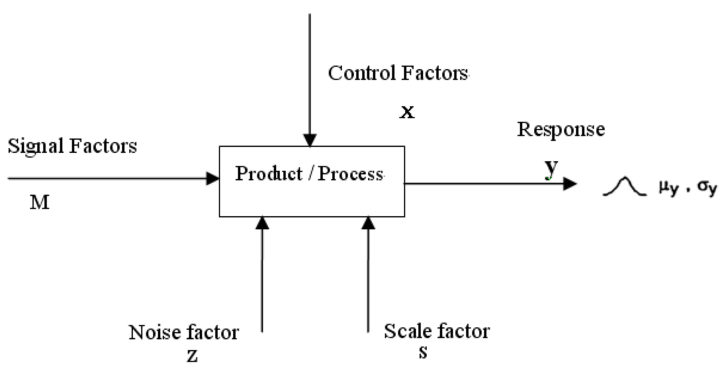

Fig. 3. Robust design with Scale factors

Step4: Analyze product structure, mapping design principal parameters to structure.

Function decomposition is needed before attribute-to-design principal parameters mapping. Using Function correlation analysis method, we can cluster analysis the differentiated products functional structure, form function module and then complete mapping of function module to product structure of the module. When the products structure is clear, by analysis of product variant mentioned above, the products public elements are determined.

Step5: Set up a parameterized flexible product platform.

Extracting public elements and flexible elements from the parametric method, parameterized flexible product platform is gained. Upon this, by adding matching and variant design element, using the element of mutual constraint and rules, the product family which meets the market demand can be realized rapidly.

3 Sample Analysis

Belt conveyor uses the conveyor belt to drive and carry load, it can be working continuously used in material conveying through the movement of the conveyor belt. Conveyor belt bypass the drive roller and tail roller, forming an endless belt. The upper and lower conveyor belt are borne by belt idler to limit sag of the conveyor belt, at the same time, tensioning device provides the necessary tension for the normal operation of the conveyor belt. Drive device drives drive roller when working, the friction between the drive roller and conveyor belt makes the conveyor belt run, the objects on belt move together with it. The construction steps of flexible platform for belt conveyor are as follows:

(1) Divide up the market grid

By analyzing the market status of belt conveyor , we know the current market is mainly divided into three parts according to their throughput, they are low-throughput, mid- throughput, and high- throughput. However, each part can be broadened horizontally according to the different width of conveyor belt, and can be divided into several series. Each series could also get a variety of variant products according to the length of conveyor belt, the height, the speed and so on. Through in depth research, the bandwidth of conveyor is divided into four scopes, they are 0.4 ~ 0.8 m, 0.8 ~ 1.2 m, 1.2 ~ 1.6 m and 1.6 ~1.8m. Figure 4 shows how to divide up the market grid.

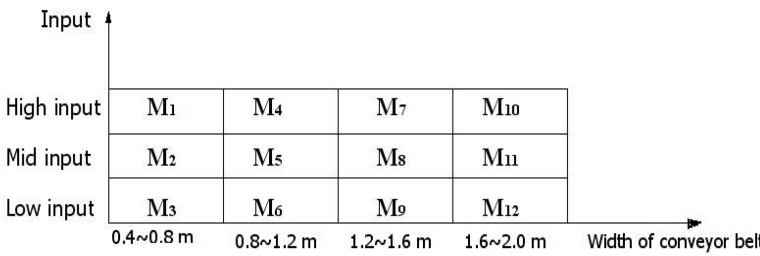

Fig. 4. The market segments of belt conveyor

(2) Analyze uncertainty and find the main parameters which determine the performance of belt conveyor, find out uncertainty factors.

When designing a belt conveyor, the main design parameters are width and speed of belt, belt idler size, roller size, bed size, the choice of tensioning devices and auxiliary equipment and so on. The factors which affect the width of belt are throughput, transmission angle, transmission speed and transmission intensity etc which are requested by users. The factors which affect the speed of belt are the changing in width of belt, throughput, transmission angle, and transmission intensity, etc requested by users. The factors which determine the diameter of drive roller are the changing in width and speed of belt. The factors which affect the diameter of belt idler are the changing in width and speed of belt too. It is obvious that all parameters are affected by bandwidth through the conclusions above, so the bandwidth is the main parameter of belt conveyor.

According to market analysis and advice brought out by experts, it is the first step to determine changing index (CVI) and coupling index (CI) using DFV. And then the desired changing curve of belt conveyor can be achieved according to CVI and CI. Finally, the optimal uncertainties of belt conveyor could be found according to the optimal trend, they are the width and speed of belt, the diameter of rollers, belt idler size and the height of bed, etc.

(3)Optimize uncertain factors, determine the range of uncertain factors, finally determine the bandwidth of belt conveyor platform, optimize the product family.

Using the design method of robust with scale factor brought out by Simpson, we can analysis the fluctuation range of bandwidth resulted from the changing in speed of belt, the diameter of rollers, belt idler size and so on, and determine typical parameter values of bandwidth when it is changing in different scales. The optimal design variables are shown as table 1.

Table 1. The optimal design variables

Series	*Band width (**m**)*	*belt speed (**m/s**)*	*Drum diameter (**mm**)*	***Roller Diameter*** *(mm)*
1	0.8	2.0	630	108
1	0.8	2.5	800	108
2	1.2	1.25	1000	133
2	1.2	1.6	1250	133
…	…	…	…	…
4	1.8	2.5	800	108
4	1.8	3.15	1000	108

(4) Analysis the structure of belt conveyor, the main parameters in designing mapping to its structure.

Determining the common elements by analyzing each series of product. We find that only the module of conveyor belt is common, in the product family of belt conveyor, other modules are all affected by parameter changing or the needs form users in some degree. So take the belt module as a common element and establish its functional structure. (Shown as figure 5)

Map the main design parameters gotten in step 2 to the structure of belt conveyer. The mappings are distributed mostly because the main parameters determine most of the parts. The modules which are determined by the main parameters entirely are shown as flexible elements, and then analyze the remaining structure modules in order to identify matching elements and variant design elements.

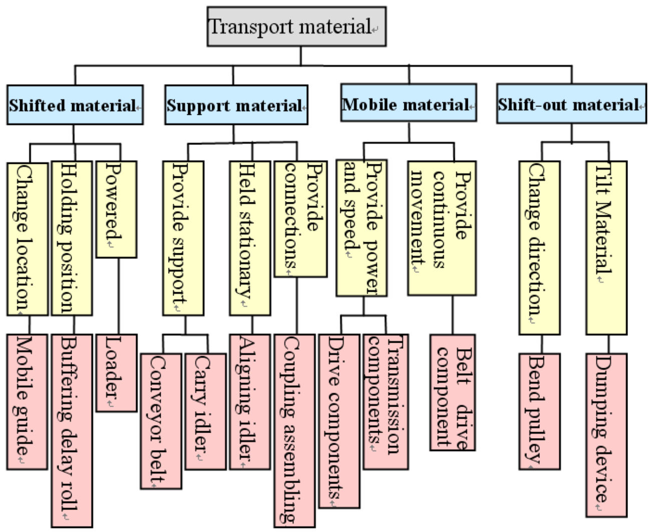

Fig. 5. Main functional tree of the belt conveyer

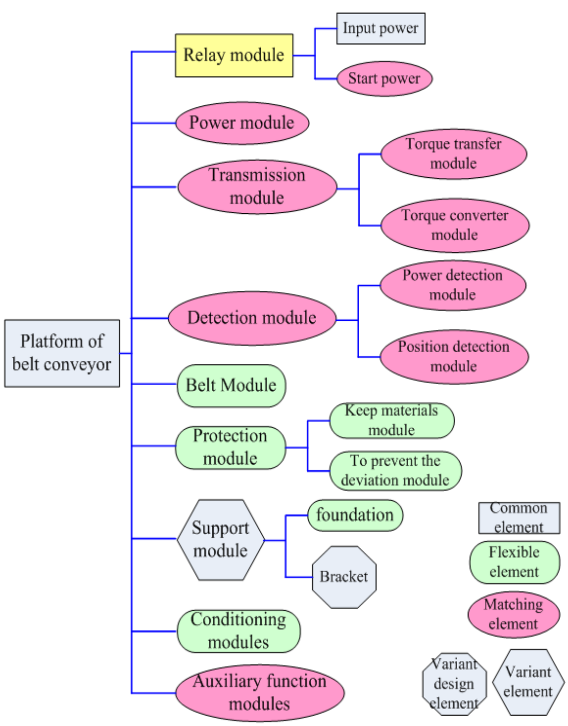

Fig. 6. The structure of parameterized flexible platform of belt conveyor

(5) Establish parameterized flexible product platform of belt conveyor

The public elements and flexible elements achieved above are taken as the elements of flexible product platform of belt conveyor. As a result, designers only adjust the value of flexible elements in product platform when some certain product is needed by customers, and then determine the matching elements according to customers' demand, finally, re-design or analog design a fraction of variant parts. By using the constraint and rules among elements, designers can configure the product quickly according to user requirements and manufacture. The structure of parameterized flexible platform of belt conveyor is shown as figure 6.

4 Conclusion

According to the research above, we have the following conclusions:

With increasing product variety and shorter development time, many companies are facing more and more complexity to develop new products. So this paper introduces a design method for flexible product platform based on parameterized.

This paper introduced a design process of parameterized flexible product platform. It begins at defining the market segments, product variants, and uncertainties. The uncertain factors are determined by the method of DFV. Parameterization is then embedded for establishing the product platform bandwidth.

Finally, a full-scale case study of product platform of belt conveyor was shown using parameterized flexible product platform.

Acknowledgments

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Early Robust Design Approach for Accelerated Automotive Innovation Processes

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Abstract. The shift to modularized cars leads to the need for early and precise concept decisions for the development of modules. Many module definitions focus on the interaction between modules to make them upgradeable. The focus here is on modules that have to work with unknown restrictions in terms of uncertainty. In this paper, emphasis is put on unknown car styling in early design stages. Because of frequent interface modifications during the validation process of car styling, the great influence of this unknown restriction on modules is discussed for kinematic systems. The systematic approach of Robust Kinematics Optimization is successively described and exemplified. Due to the early and computer-aided consideration of uncertainties, the developer is able to judge even very unconventional and innovative module concepts. Furthermore, a higher level of transparency is achieved in concept decisions because the consequences of modifications during later development stages have been precociously integrated and validated.

Keywords: Early Design Stage, Integration of Innovation, Robust Design Optimization, Automotive Development Process.

1 Introduction

In recent years, the automotive development methods have moved from hardware-dominated application and testing to virtual validation of vehicles, systems and components. As a result of lower costs for software compared to hardware, this strongly downsizes or even eliminates hardware testing phases in standard development processes. Due to additionally decreasing product development times in combination with extending numbers of platform derivates, one of the major current challenges in the automotive industry is the need for precise, rapid and robust concept decisions in early design stages. Therefore, new approaches and methodologies in terms of computer-aided innovation are needed in order to increase the maturity of virtual validation.

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1.1 Early Design Stages in Styling-Driven Automotive Industry

Current development standards are characterized by simultaneous development phases. The actual development as shown in fig.1 is usually structured into the phases "strategic development", "preliminary development" and "mass-production development". In this paper, the focus strictly is on the early stages of strategic and preliminary development as computer-aided innovation (CAI) unfolds most impact there [12,16].

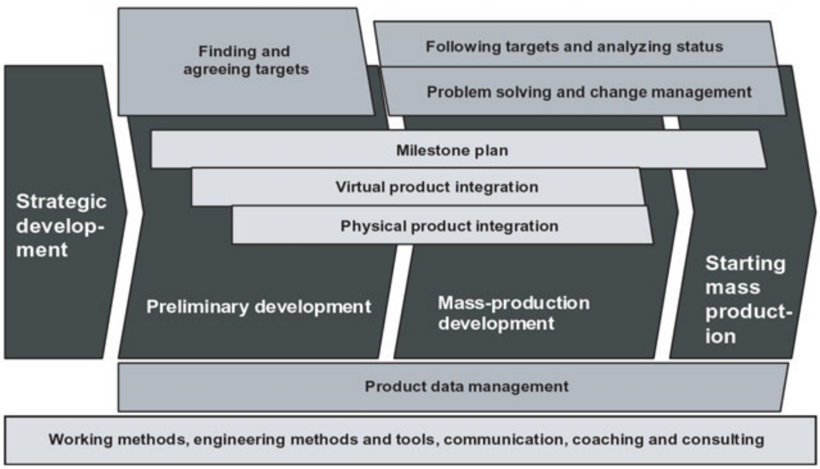

Fig. 1. Overall illustration of the product generation process [17]

Especially in the automotive industry, there is a huge difference in terms of standard timetables and processes between a new-, change- or adaptation car design. Therefore, most companies established adaptive standard processes distinguishing between new car projects, successor car projects and model upgrading projects [2].

Although the standard processes for developing the entire car might differ, the thought of unitized cars from component's perception is more and more commanding in today's car development. Unitized car means that a vehicle is assembled by a certain amount of modules (gear boxes, bumpers, breaks, seats, actuators for automatic tailgates, etc.) [19,20]. [9] underline the necessity of modular product architecture especially when the development of complete subsystems or components is performed by different teams in different locations. This is the case in the automotive area, where a lot of systems and components are coming from suppliers. The goal is that the modules are standardized comprehensively within an OEM and can be adapted specifically for each car project. Additionally, from the engineering point of view, module based product development contributes to a better management of complexity, makes parallel product development possible and enables better control of future uncertainties [4]. The latter is possible because modules can be seen as "functional black boxes", which can be developed and tested separately. However, a clear definition of the interfaces between the modules and their environment is a prerequisite to benefit from the module approach [9]. With this in mind, [15] “consider complex products as a network of components that share technical interfaces in order to function as a whole”.

This module paradigm leads to reduced costs because of scaling effects. But usually, the development of the 1-2 standards for each module bases on experience and expertise of engineers and does not necessarily integrate the influence of new car projects. This might eventually lead to suboptimal results if the styling of new cars leads to unconsidered effects for the modules themselves, see fig. 2.

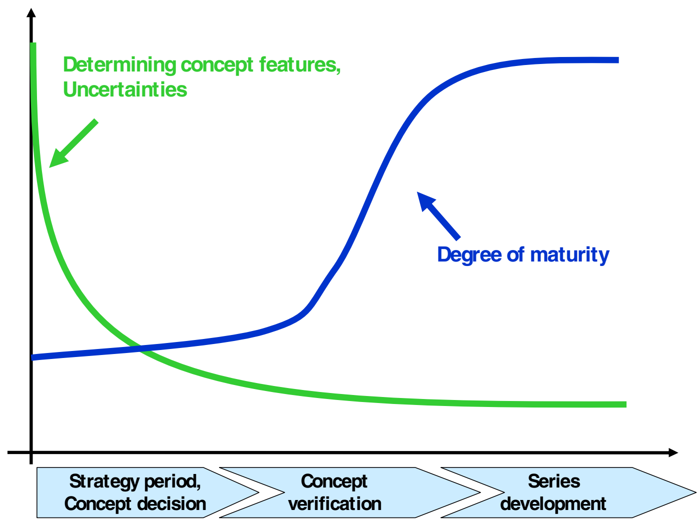

Fig. 2. Basic dilemma of module concept decisions

Furthermore, new inventive methods like TRIZ are eager to help both suppliers and OEM’s to reach unconventional solutions for modules beyond the previous experience of the engineers. But the advancing implementation of those methods discussed in research works such as [6] only will establish and unfold their full power, if all uncertainties are precociously validated.

1.2 Kinematic System Modules in the Automotive Industry

Especially modules that are directly dependent on the styling of the car are often faced with improvable behavior of early developed module concepts when it comes to the mass-production development. One example being investigated within this paper are the modules that one can aggregate by so called „kinematic systems“. In this paper, kinematic systems are defined as multi body systems containing nonlinear movements, which are usually characterized by a closed mechatronic system behavior. Namely, it’s window lifters, retractable tops or automatic rear lids and tailgates. Those modules are typified by a high degree of customer visibility. Hence, interface modifications regarding car styling become very likely in early development stages. However, those modifications can have a direct effect on the performance of the module systems. Investigated modules often showed high sensitivities of interface parameters concerning the entire system behavior. Moreover, kinematic systems are not developed and produced by the original equipment manufacturers (OEM) themselves but are mainly left responsible at the suppliers both during production and development stages. The behavior of the entire kinematic system still remains within the responsibility of the OEM's which additionally brings challenges in terms of shared development [18].

1.3 Early Evaluation Loops of Kinematic Systems

In fact, the development of innovative modules requires very early evidence about the fulfillment of functional requirements in partly very different car concepts. For this purpose, the boundary conditions of similar- or predecessor car concepts are being consulted. On this basis, simulations should verify the operability for the target car concepts.

For the computation of such mechatronic systems, CAE programs are already established. In accordance with verified input parameters and validated simulation models, evidence about the behavior of one model draft can already be given. This approach has proven successful in the analysis of systems that are yet mass-produced [14]. Unfortunately, these investigations discount the following uncertainties, which are immanent regarding the standard methods:

1. Decisions of management regarding the car styling in the context of the model validation process.
2. Poor data availability of car components during early development stages (strategic und preliminary stage).
3. Uncertainties due to CAD methods: Difficult data gathering of hybrid, complex assembly structures.
4. Uncertainties due to verification methods: Simulation models of new, innovative module concepts can only be validated separately from the car or interface context. The gap between module behavior in the laboratory and in the car is not taken into account.

At this point, the necessity for a new computer-aided approach becomes obvious. This approach has to help innovative module concepts to a considerably higher degree of maturity in early design stages as well as it has to bring more transparency throughout the whole automotive model styling validation process.

The problems shown before affect some different aspects of computer-aided innovation. Recent research activities like [7] intensively investigated the question of how to systematically come to innovative or inventive products. The increasing applicability of methods like TRIZ enables developers of automotive modules to reach a higher level of inventiveness during the very first stages of development. However, the demanding functional requirements of the automotive industry combined with the high sensitivity for uncertainties leads to problems of inventiveness-driven tools established lately. As a consequence, engineers tend to fall back to proven and tested conventional modules. To support the engineer within this basic dilemma, tools of parameterization and automation emerged. One example is design automation (DA) discussed in [8]. Based on explicit information of existing parts, concepts can be rapidly adapted to different boundary conditions. Other approaches of parameterization like [10] enable the automatic investigation of different designs. However, all investigated computer-aided innovation methods do not regard uncertainties of the development process. The handling of strategic uncertainties is topic of [11]. But the very generic view on uncertainties disallows the implementation in terms of mathematical-based CAI.

2 RKO – Robust Kinematics Optimization

During research on this computer-aided innovation approach, two fundamental questions were figured out:

1. How to ensure that the competing module concepts for kinematic systems are evaluated with their optimal parameters?
2. How to manage uncertainties in the early design stages?

Basically, these questions address the problem of how uncertainties in early stages of a module development can be evaluated systematically as well as how the impact of uncertainties can be reliably minimized. This elementary topic has been investigated in the area of Robust Design Optimization (RDO) for a while. Following, the basics of RDO are explained in order to illustrate the necessary adaptations to be able to evaluate robustness of kinematic systems and to optimize the behavior and performance of arbitrary module concepts in early design stages.

2.1 Basic Idea of Robust Design Optimization

Originally, the idea of the Robust Design Optimization (RDO) developed from classical optimization strategies, which optimized components in topology or shape according to defined objective functions. However, since uncertainties in the mass production (e.g. variations in terms of material properties, component geometry) were ignored, a higher percentage of scrap was the result of unconsidered and unexpected deviations in series process. To minimize the high costs of meeting the target quality, the idea of a zero-defect production established itself. This paradigm is not focused on the optimization of production processes, but on the optimization of the component design in order to make the design insensitive to possible variations in mass production. For this purpose, all relevant parameters are afflicted with production-specific tolerances. Subsequently, the impact on the fulfillment of the objective functions is determined. At this point, literature distinguishes between "Robustness evaluation" ($<\pm 2\sigma$) and "Reliability Analysis" ($<\pm 6\sigma$) [13]. In order to carry out an assessment in the area of Reliability Analysis ($<\pm 6\sigma$), very accurate knowledge on the considered production process is needed. Since this is not possible in early design phases, all further analyses of variance in this paper are limited to a safety level less than $\pm 2\sigma$.

Basically, a RDO task contains a set of m design parameters

$$\boldsymbol{d} = [d_{1,l}, d_{1,h}, d_{2,l}, d_{2,h}, \ldots d_{m,l}, d_{m,h}] , \quad (1)$$

that are afflicted with defined variation boundaries di,l, di,h . In addition, r variances

$$\boldsymbol{r} = [r_1, r_2, \ldots r_n] \quad (2)$$

are defined. ***r*** contains scattering of design parameters as well as of parameter which cannot be influenced by development. Ordinary RDO approaches work in a dual-looped process. First, the robustness value $\delta_R(\boldsymbol{d},\boldsymbol{r})$ of one random set of design parameters inside its boundary conditions is determined within the inner loop. Second, the design parameters ***d*** are given other random values and the robustness is re-evaluated. The second, outer loop is usually done by stochastic optimization algorithms such as genetic algorithms, Monte Carlo simulation or particle swarm optimization. The target *T* of the RDO process can simply be identified as

$$T(\mathbf{d})=\min(\delta_R(\mathbf{d,r})) . \quad (3)$$

In other words, the robustness value δ_R as indicator to the overall sensitivity of output parameters versus input parameters has to be as small as possible. Then, scattering ***r*** exerts minimal influence on the output and functional requirements, respectively [3].

2.2 Definition of Robustness

The major challenge within RDO is the inner loop being responsible for the valid evaluation of robustness. Basically, all determination methods for robustness values refer to the values of the output probability density function like shown in fig. 3.

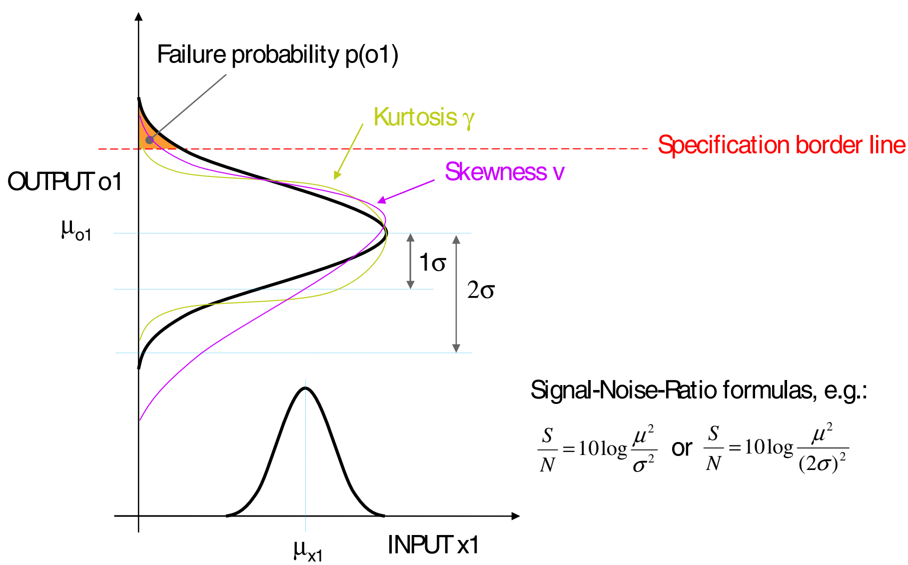

Fig. 3. Possible scattering of one output due to input deviations

Conventional methods like Taguchi's loss function interpret the variation from the expected mean value μ_{o1} as actual monetary loss and hence try to minimize deviation of predicted output values from target values [5]. Other approaches minimize failure probability $p(o_1)$ or assess statistical parameters of the output distribution function like mean value μ in ratio to standard deviation σ, skewness ν or even kurtosis γ.

These default approaches measure robustness on the basis of one or more outputs and cumulate the single robustness values resulting in an overall robustness. This method has proven successful in Finite-Element-Analysis-dominated RDO research. However, RDO focuses on the early consideration of production tolerances but not on the special challenges of early design uncertainties. Furthermore, the rating of one output in terms of the result of FEM simulation is not sufficient regarding the robustness evaluation of kinematic systems.

2.3 Robust Kinematics Optimization

The reason for this is that the development process of kinematic systems is not only based on the fulfillment of strict functional requirements regarding performance (e.g. opening times) and applied loads, respectively. Rather, the behavior of the entire system afield has to become the fundamental development principle. Thus, Robust Kinematics optimization (RKO) as further development to RDO extends the evaluation dimensions in order to determine robustness considering kinematic parameters like opening angles. Fig. 4 shows the example of an output value o1. Illustrated in grey color, a couple of probability density functions of o1 are shown for different opening angles β. By interpolation between the probability density functions it is possible to analyze the behavior of statistical parameters. E.g., the characteristics of the mean value $\mu_o(\beta)$ can easily be visualized, see red curve in fig. 4.

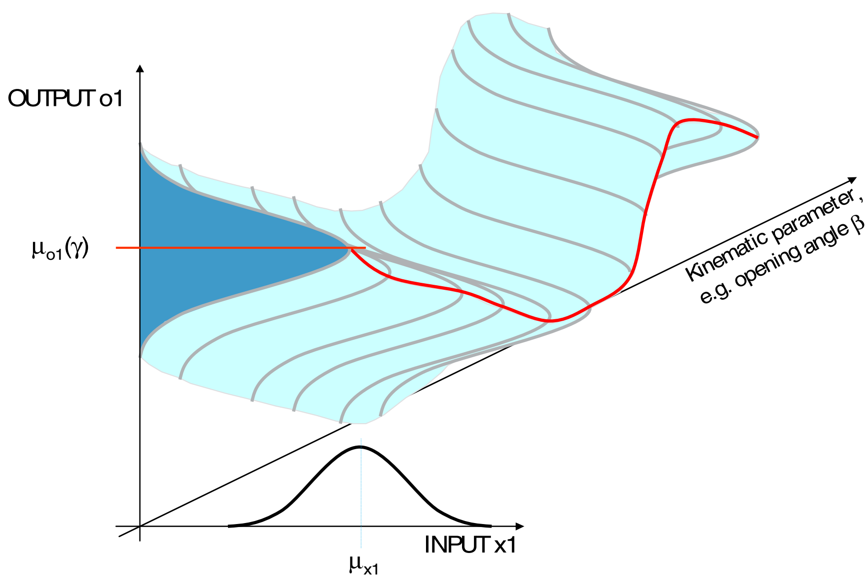

Fig. 4. Dimension extension of the robustness evaluation process in the framework of RKO

For instance, let the computed standard deviation 2σ of an arbitrary output parameter o_i be considered as good regarding robustness when the kinematic system is closed (β=0). Subsequently, RKO investigates the behavior of 2σ plotted against the opening angle. If the robust standard deviation 2σ drifts from its original value, the investigated set of design parameters has to be considered less robust as it would have been conventionally assumed. Simulation results showed that the computed robustness values (e.g. 2σ, μ, p(o_i)) differ considerably when assessed over an entire kinematic parameter. Only with this further step in addition to RDO the systematic investigation of robustness of behavior for kinematic systems becomes possible.

The computer-aided innovation based on RKO envisions the following systematic approach.

1. Specification of robustness: Initially, the bounds for allowed robustness value drifts have to be determined for each investigated use-case and functional requirement output, respectively.
2. Specification of design space: The simulation model of the considered module concept is given initial design parameters $\mathbf{d_1}$ which contain reasonable parameters for the interface, i.e. styling of a predecessor car compatible best to the intended car projects for the investigated module concept. Furthermore, design space in terms of boundary conditions $\mathbf{d_{i,l}}$, $\mathbf{d_{i,h}}$ have to be determined on basis of the experience made in previous car projects.
3. Specification of uncertainty: The next step integrates the special needs of early design stages by defining uncertainty or scattering values **r**. Those uncertainties can be relatively large as one module concept should fit into possibly every future car containing the investigated kinematic system framework. Additionally, the values of **r** are usually interdependent.
4. Optimization of robustness: Once uncertainties have been systematically built, the overall robustness of initial design parameters $\mathbf{d_1}$ can be determined. Following, the actual optimization takes place. Therefore, the upper and lower bounds of all design parameters have to be adapted. Those bounds again are usually interdependent due to different car types. At this stage, everything is prepared for a stochastic optimization. The goal of the optimization is to find the optimal design parameters of the module concept $\mathbf{d_m} \in \mathbf{d}$ that represent maximum robustness of the behavior of the kinematic system when afflicted with uncertainties due to early design stage problems. Thus, the systematic robustness evaluation of step 3 has to be done after every optimization step. Regarding minimal influence of the robustness of the optimization algorithm itself, genetic algorithms as evolutionary computational tools fit best as they showed good results in related works [1].

2.4 Example

To illustrate the approach of RKO shown in section 2.3, the method is applied on an example for kinematic system modules. For this purpose, automatic tailgates as shown in fig. 5 are qualified best. This is because the influence of different target car types and styling decisions on automatic tailgates is unquestioned in course of the automotive development process.

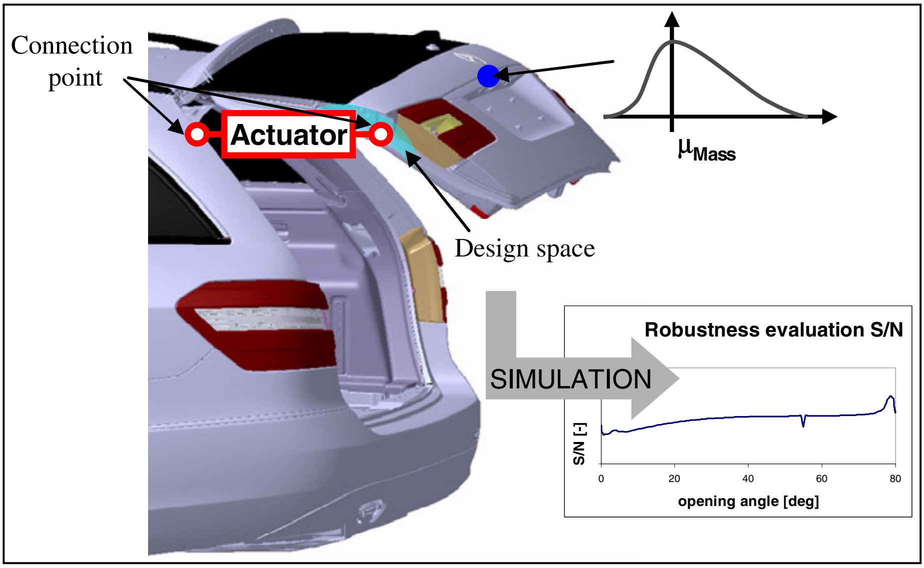

Fig. 5. Simplified model of an automatic tailgate

The following explanations are held simplified in order to make RKO tangible within this paper. However, the main idea remains the same also for the complex overall optimization process for kinematic systems.

1. Specification of robustness: Based on very intense adjustment talks with experienced engineers, the considered robustness values as well as their respective drift penalties have to be determined. This must be done once for a kinematic system in course of the definition of functional requirements for the entire system. Later, module developers will access the limit definitions without higher efforts. The given example for robustness value drift will be the simple Signal-Noise-Ratio

$$S / N = \mu / \sigma \quad (4)$$

   of the necessary torque of a spindle actuator that moves the tailgate plotted against the opening angle.
2. Specification of design space: As soon as module development has decided on the targeted car types, the design boundaries have to be determined. E.g., automatic tailgate concepts for sports utility vehicles (SUV) as well as for station wagons contain elements that apply forces from the Body-in-White (BiW) to the tailgate. The location of the connection points of those elements plays a big role regarding kinematic behavior. Usually, the possible locations for connection points at the BiW can be illustrated as half-opened cylinders. The radius and possible bending of the cylinders strongly correlate with the investigated car type. Hence, the design parameters depend on the car type and have to be defined relatively. To start RKO, initial design parameters are adopted from the concept most similar to the targeted car types, e.g. the latest SUV. In case of unavailability of similar starting points, arbitrary initial parameters can be taken as long as they stay within the boundary design conditions.

3. Specification of uncertainty: One of the most obvious uncertainties of automatic tailgates comes from the design process of the tailgate itself. Namely, the weight of a hardware-tailgate usually differs significantly from the original assumption of early design stages. Furthermore, interdependent scattering parameters can be identified for automatic tailgates. Module concepts of automatic tailgates have to be capable of actuating the tailgates of an SUV as well as of a station wagon. Since the tailgate shapes essentially differ between an SUV and a station wagon in terms of thickness, mass, slope and especially interface design, the styling uncertainties included in $\mathbf{r}$ depend on the car type. This means that the design constraints of BiW that build the main interface uncertainties to the module vary subject to the car model. In order to attract as many customers as possible, the design of cars is strongly based on styling decisions. Those styling decisions are typically made on top management level and seek to include future trends and needs of customers. In opposite to design uncertainties like weight predictions, styling uncertainties cannot be derived from experiences. On the one hand, sharp ranges and borders of scattering functions can hardly be determined. On the other hand, uncertainties of early design stages are never exactly specified regarding their borders or distribution. I.e. borders of weight prediction are estimated and hence represent a trend, though more precise than styling predictions. The underlying approach of RKO strives to optimize a system's robustness on the basis of uncertain parameters. As those uncertainties remain constant over the optimization process, robustness values are compared not absolute but relative to each other in order to find the best system parameters. Hence, trends in styling can be included in RKO even if their parameters are rather predicted qualitatively. Based on estimations of styling departments, the main challenge is the complex formulation and parameterization of those highly interdependent uncertainties.
4. Optimization of robustness: The double-looped optimization process firstly evaluates the robustness of the entire system. For the simplified example investigated in this section, the initial design parameter combination $\mathbf{d_1}$ is established with the connection points for force-applying elements of the last SUV or station wagon released to the market. Then, uncertainties like deviation in mass or scattering of the above-mentioned connection points are applied. Subsequently, a robustness evaluation algorithm samples a certain amount of stochastic combinations of uncertainty deviations. The actual robustness values are determined by investigating the scattering of the necessary torque in terms of identifying the 2σ-level. At this point, genetic algorithms start to mutate and crossover design parameters within their bounds and the robustness can be re-evaluated with a new set of design parameters. The final result of this evolutionary optimization will be a combination of design parameters with the minimum-possible 2σ-level of the necessary torque plotted against the opening angle of the tailgate. I.e. that evolutionary algorithms find the one design parameter set $\mathbf{d_m}$ for an arbitrary module concept which is optimal robust against all uncertainties brought by the early design stage dilemma.

2.5 Contribution to Computer Aided Innovation

The implementation of the RKO standard introduced in section 2.3 enables the developers of standard modules to establish a considerably higher level of maturity and transparency during early design stages. The major input for the developer is uncertainty due to early design stage. These uncertainties have to be disclosed and discussed in the framework of module development. Furthermore, the degrees of freedom for module design parameters $\mathbf{d_m}$ have to be presented openly. Once all parties agree to the assumptions, the developer is free to test established module concepts as well as very creative and inventive concept drafts. This is because the holistic approach of RKO allows the rapid investigation of innovative ideas within the framework of clarified and visible boundary conditions. See fig. 6.

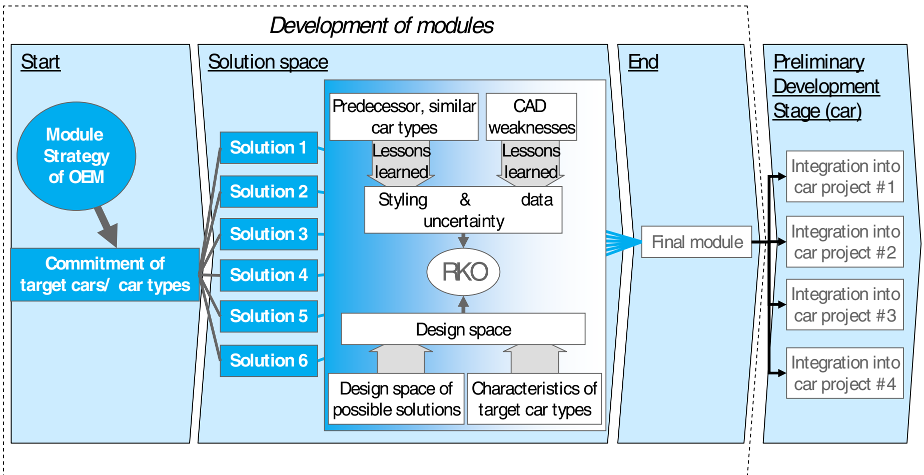

Fig. 6. Integration of RKO into standard automotive development process

Of course, the uncertainties considered in the earliest design stages narrow in the course of later development stages. But having assured that the designed module fits best into the targeted cars and is optimally robust against immanent uncertainties during car development, the degree of maturity necessarily increases further in later development phases. This means that the behavior of outputs becomes even more robust because input deviations decrease. The behavior of outputs is equal to the fulfillment of functional requirements. Hence, late design decisions have a minimal influence on the fulfillment of functional requirements and the necessity to change functional requirements of automatic tailgates is minimized. Ultimately, the high degree of transparency offered by the method of RKO leads to more sustainability in management decisions because all participating parties had to commit to the boundary conditions for module development in early stages.

3 Conclusion

This paper started with a classification of module-based development in the course of early design stages in the automotive industry. Subsequently, kinematic systems in the automotive industry were introduced representing a special class of modules that are usually faced with high uncertainties of interface design due to frequent exterior styling modifications. The basic dilemma of high uncertainties versus the need for precise concept decisions of large-scaled modules lead to the need for a systematic, computer-aided approach that enables innovative modules to unfold their full abilities of modularization. Established CAE technologies in the area of Kinematic systems neglect design parameter variations as well as uncertainties in the later course of product development. The needs for variation of parameters and consideration of uncertainty within the development of Kinematic system modules have been investigated in the area of Robust Design Optimization for a while. Therefore, the research effort within this paper focused on the necessary modifications in order to introduce Robust Kinematics Optimization. The envisioned process shows the high unique effort necessary for the implementation of Robust Kinematics Optimization as well as the huge benefits for every further development of modules. The idea of this computer-aided innovation was afterwards illustrated using the example of automatic tailgates as highly styling-dependent modules. Finally, the impact of Robust Kinematics Optimization was shown. Because of higher transparency as basis for concept decisions in early design stages, the developer may unfold and consider all possible and also unconventional concept ideas as all usual uncertainties are integrated in this computer-aided innovation approach.

Exterior design decisions are usually made regarding the appearance of a whole car. Recent experiences showed that the assumptions made for styling uncertainties are only relevant as long as the design strategy remains constant. Unfortunately, the customer’s decision is dominated by the judgment over the car styling, especially in the luxury segment. Subsequently, modifications or evolutions of the car styling will remain an immanent aspect of the car development as the customer’s opinion is volatile. Eventually, the uncertainties agreed by the management also remain afflicted with uncertainties. But with the systematic approach of Robust Kinematics Optimization, the developer is able to quickly handle changed circumstances and re-evaluate his decision.

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The CAI-NPD-Systems Maturity Model as Forecasting Method: From Closed CAI 1.0 to Holistic CAI 2.0 Solutions

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Abstract. This article examines current and future developments in the field of CAI using a model called "CAI-NPD-Systems Maturity Model". This model is based on two aspects of the CAI systems development: The development in innovation theory and models such as Stage Gate or Open Innovation, and the development in the technologies-supporting software approaches such as Web2.0 to develop new generations of CAI. As a result, an evolution path from generic IT-support and simple ad-hoc NPD-processes over closed CAI systems to holistic CAI2.0 is proposed. Examples and implications of these trends are specified.

Keywords: Closed CAI 1.0, Closed CAI 2.0, Open CAI 2.0, Computer Aided Innovation, Open Innovation, Closed Innovation, Web 2.0, Crowd sourcing, Open Innovation Accelerators, OIA, New Product Development, NPD, CAI-NPD-Systems Maturity Model.

1 Introduction

So far, even holistic CAI-tools in existing categorization schemes were and are primarily focused on firm-internal New Product Development (NPD) concepts like Employee-Driven-Innovation (EDI) and Closed Innovation [1-7]. Their prime concern is to support the organization's own employees and the process of management from invention to innovation by providing methods such as TRIZ, idea or project portfolios, suggestion schemes or variations of the stage gate model. External stakeholders of the innovation process such as customers, users or other interaction with people and organizations outside the company has not played a decisive role in the traditional CAI-concepts so far. Therefore, these traditional CAI-approaches for the closed innovation process are here referred to as "Closed CAI 1.0".

However, due to technological as well as strategic changes, new types of CAI systems emerged. From a technological point of view the use of recent internet programming technologies, i.e. Ajax, RSS feeds and other developments around the Web 2.0-paradigm, allowed a more interactive and intuitive use of web-based applications and therefore opens the access to CAI to a larger audience of

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non-professional and untrained users [8-13]. From a strategic point of view companies shifted from the predominantly closed innovation paradigm of the past to the recently popularized open innovation paradigm, and started to inter-act with people and organizations outside the company in order to harvest their innovative capabilities [13-16]. Both developments support each other and led to the widespread growth of various intermediaries that offer web-based platforms and tools on the basis of latest web 2.0 technologies to offer companies access to innovation communities [17]. This development is here referred to as “Open CAI 2.0”, which represents the next evolutionary step in the CAI development.

Although, these categories in the CAI development are helpful to distinguish present generations of CAI, they lack a common theoretical underpinning and a framework that would allow forecasting their future development. This paper aims to further develop the “CAI-NPD-Systems Maturity Model” described by Waldmannstetter and Hüsig [6] or Hüsig and Kohn [3] which is based on and inspired by similar approaches, such as those by Bowden [1], Cooper [18, 19] or McGrath [20]. This framework presented here aims to describe, explain and even extrapolate the CAI evolution pattern from “Closed CAI 1.0” to “Holistic CAI 2.0 Solutions”.

The paper will be structured as follows. First the CAI-NPD-Systems Maturity Model is briefly described and past and present CAI-tools, categories and NPD-methods are exemplified. Building on these trends, a possible future CAI-roadmap is suggested and new possible stages in the CAI-NPD evolution are integrated into the CAI-NPD-Systems Maturity Model. Implications for new and old CAI-suppliers according to the proposed roadmap including their opportunities and threats are provided.

2 The CAI-NPD-Systems Maturity Model

Scholars in process management and information systems have developed a long tradition of analyzing the development of IT usage or process capabilities by what are called maturity or stage models [21, 22]. Maturity models typically consist of a structured collection of elements that describe certain aspects of maturity in an organization. A maturity model can be used as a benchmark to assess different organizations for comparison and is frequently organized in hierarchical stages or levels. One well-established example is Humphrey’s Capability Maturity Model (CMM) [21], which is a process capability maturity model to aid the definition and understanding of an organizational process. In the area of CAI and NPD systems, similar approaches are also starting to become popular, such as those by Bowden [1], Cooper [18, 19] or McGrath [20].

For the further development of the CAI field, these models could be important for the formative period of the knowledge creation in the CAI field in three ways: First, CAI-NPD maturity models could provide an orientation for future strategies of both CAI suppliers and developers, and guide buying or implementing decisions by users. Second, these models are also interlinked with the process and management aspects of NPD, thus emphasizing a more holistic approach to CAI system development. And finally, those frameworks could be used as a common theoretical underpinning and a framework that would allow forecasting the future development of CAI and NPD systems like the "CAI-NPD-Systems Maturity Model" described by Waldmannstetter and Hüsig [6] or Hüsig and Kohn [3].

The basic propositions of the CAI-NPD-Systems Maturity Model are based on the idea that the need for improvement of the organizational innovation system can be described by the distinctive benefits of the IT-support and the NPD methods used. However, these basic propositions of the model have not been explicitly stated or formalized so far. This further step in formalizing is done here. The starting point to do so are the potential benefits of CAI tools, which can be categorized as efficiency, effectiveness, competence and creativity enhancing [3, 4, 6]. These potential benefits can be summarized as part of the *supporting capability* which ultimately increases the *innovation success* of firms [6]. This forms proposition 1:

P1: A higher *supporting capability* increases the *innovation success* of the firm.

The extent to which the potential benefits of CAI systems can be realized depends positively on the level of CAI-category or CAI-Stage and the ability to use the functionality effectively. The technological CAI-stage and the organizational ability to use the functionality of CAI systems effectively are defined as *CAI maturity*. Therefore, this is presented in proposition 2:

P2: A higher *CAI maturity* increases the *supporting capability* of the organization.

Along the lines of the CAI maturity, also the NPD maturity concept assumes that the more elaborated the NPD methods an organization is able to use successfully, the greater the *NPD maturity* of that organization will be. Furthermore, a greater NPD maturity would translate into a greater supporting capability for the ultimate innovation success. This is summed up in proposition 3:

P3: A higher *NPD maturity* increases the *supporting capability* of the organization.

And finally, since most CAI tools are targeted at an explicit NPD task or a process stage, it is assumed that it is necessary to select carefully and match the right tool with the adequate method for the right task and phase of the NPD process as long as the CAI tool is not a holistic solution [3, 6]. Still, in case of a holistic solution, also a comprehensive NPD-system would be needed to effectively support and utilize it. Moreover, even in this case, the maturity level of the NPD system must be analyzed to provide a sufficient match between CAI and NPD capabilities. Unless CAI or NPD methods are embedded in people's work and processes, it will not be used and their benefits will not be realized. Therefore, the fit between the CAI and the NPD maturity influences the combined CAI-NPD-systems maturity which increases the supporting capability and ultimately the innovation success of the firm. The *CAI-NPD-systems maturity fit*'s influence is described in proposition 4:

P4: A higher *CAI-NPD maturity fit* increases the positive effect of a higher *CAI maturity* and *NPD maturity* on the *supporting capability* of the organization.

A conceptual model of the basic propositions of the CAI-NPD-Systems Maturity Model is presented in figure 1.

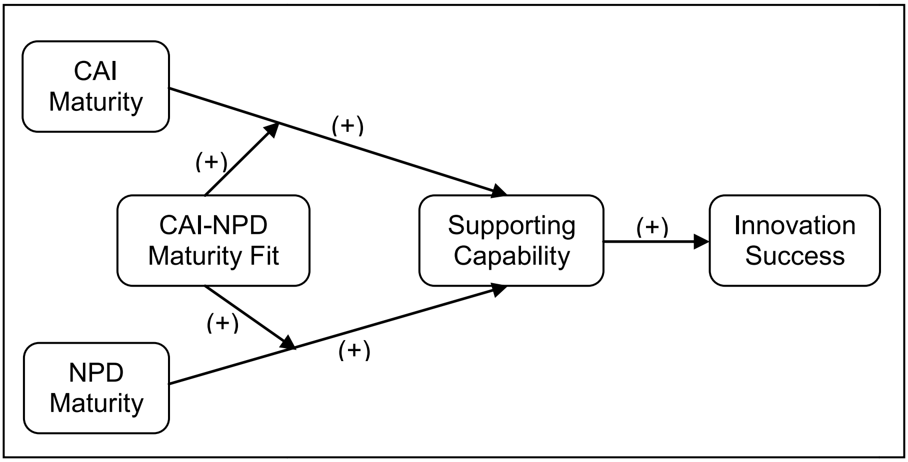

Fig. 1. A conceptual model of the CAI-NPD-Systems Maturity

2.1 NPD Maturity

To support this matching process, maturity models for the NPD process developed by Cooper [18, 19] or McGrath [20] might be helpful. In this model, Cooper [18] proposes different maturity stages, which an organization's NPD system must typically pass through. These stages are seen as a kind of natural evolutionary path down which an organization has to go through in its NPD capabilities. The stages are termed "generations", which start at the lowest level with an unmanaged NPD process and ad hoc innovation activities followed by a first generation scheme called "phased review process". In this stage, which was pioneered by NASA in the 1960s and later adopted by the US military, the NPD process is focused on technical milestones only and fails to integrate other functions or customer inputs [18]. The next stage is characterized by like Stage-Gate systems. Firms that use second-generation NPD processes like Stage-Gate systems can overcome some of the limitations of the initial stage and include cross-functional mechanisms and stronger market orientation. The highest level is reached when firms implement a third generation NPD process which is faster, parallel and more flexible than those from the second generation. A third generation NPD process is presented in figure 2.

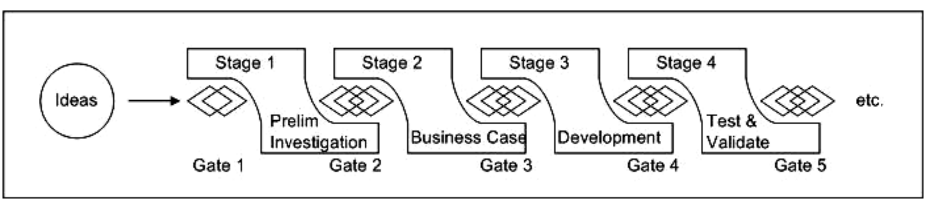

Fig. 2. A third generation NPD process [18, 19]

According to the logic of the NPD maturity concept, every increase in the generation assumes that the more elaborated the NPD methods and processes an organization is able to use successfully, the greater the NPD maturity of that organization will be, which would translate into a greater supporting capability for the ultimate innovation success. This logic is presented in figure 3.

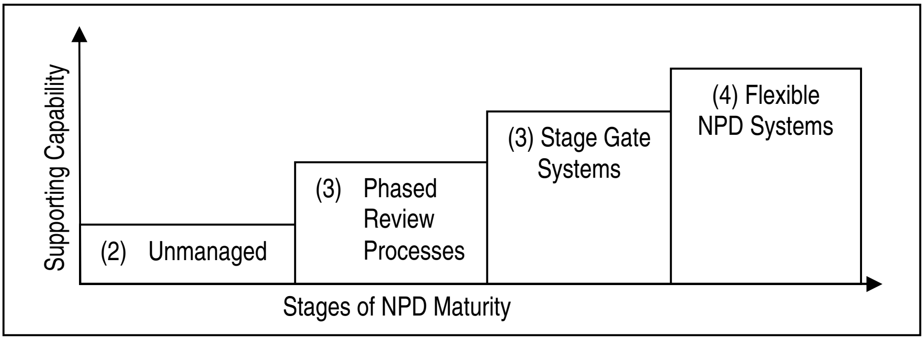

Fig. 3. Stages in NPD-Systems Maturity [6, 3]

2.2 CAI Maturity

On the basis of the NPD-Systems Maturity stages, appropriate CAI system stages to the maturity of the NPD system were adjusted [6, 3]. To do so, also the CAI systems are organized into a maturity model to match the two systems. As seen in other areas of information systems, also in CAI a tendency towards increasing system integration over formerly separated tools, processes and applications to archive higher levels of ideality is assumed even if not accomplished in all aspects [2, 22]. Using Bowden's [1] maturity model for CAI and combining it with the CAI categorization of Kohn and Hüsig [10], Waldmannstetter and Hüsig [6] organized the maturity of CAI systems into the following stages:

- Stage 0: The organization has no IT-enabled NPD process or uses generic software tools like Excel or Email to support the NPD activities.
- Stage 1: People in the organization are using focused tools for specific NPD tasks, e.g. project management or mind mapping tools.
- Stage 2: Organizations have more holistic solutions that cover the whole process and related activities. The NPD process is widely captured in the IT system. Sopheons Accolade, ID, IntraPro Innovation by XWS or Hype IMT offer integrated CAI solutions which fit into this category.
- Stage 3: Organizations integrated all relevant NPD processes across different business units and departments, and connected other firm process and systems with their CAI system. Unilevers Innovation Process Management System (IPM) or SAP with SAPxPD are said to have achieved that status.

Along the lines of the NPD maturity, also the CAI maturity concept assumes that the higher stage in the CAI development, the greater the CAI maturity of that organization will be. A greater CAI maturity in turn translates into a greater supporting capability for the ultimate innovation success. This logic is presented in figure 4.

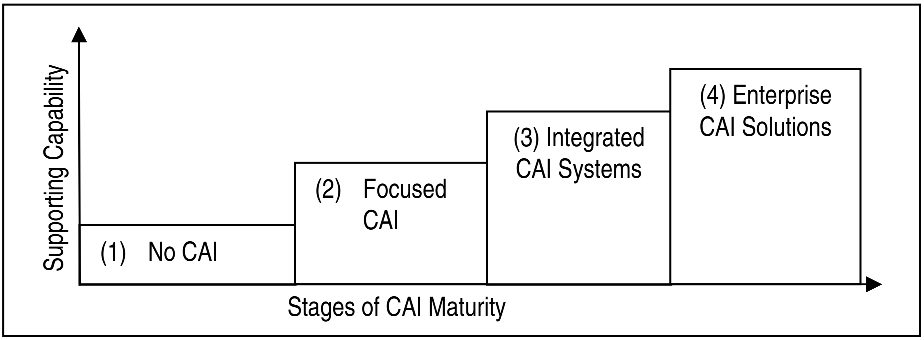

Fig. 4. Stages in CAI-Systems Maturity [6, 3]

Hüsig and Kohn [6] propose that in this maturity model the stages can also be seen as a kind of natural evolution path along which an organization has to proceed. Therefore, this model suggests a staged introduction of CAI tools with respect to the actual stage.

3 The Updated CAI-NPD-Systems Maturity Model

The CAI-NPD-Systems Maturity Model as described above is mainly focused on the Closed Innovation paradigm and the Closed CAI 1.0 concept. Therefore, the original model needs to be expanded and is used to further develop the CAI-NPD-Systems roadmap. This adds new stages of maturity on both sides of the model – CAI and NPD capabilities.

3.1 New NPD Maturity Stages Based on Open Innovation

First the maturity stages of the organization's NPD system is proposed to be expanded by the Open Innovation concept [13-16]. Open innovation is defined as the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for external use of innovation, respectively [13]. This paradigm assumes that firms can and should use external ideas as well as internal ideas, and internal and external paths to market, as they look to advance their technology. This concept was coined by Henry Chesbrough, based on his research on the innovation practices of large multinational companies. Open innovation is characterized by cooperation for innovation within wide horizontal and vertical networks of universities, start-ups, suppliers, spin-offs, and competitors [14]. Companies can and should use external ideas as well as those from their own R&D departments, and both internal and external paths like spin-offs or licenses to the market, in order to advance their technology are displayed in figure 5.

Since sources of external information for the innovation process are plentiful, including market actors like customers, suppliers, competitors; the scientific system of university labs and research institutions; public authorities like patent agents and public funding agencies; and mediating parties like technology consultants, media,

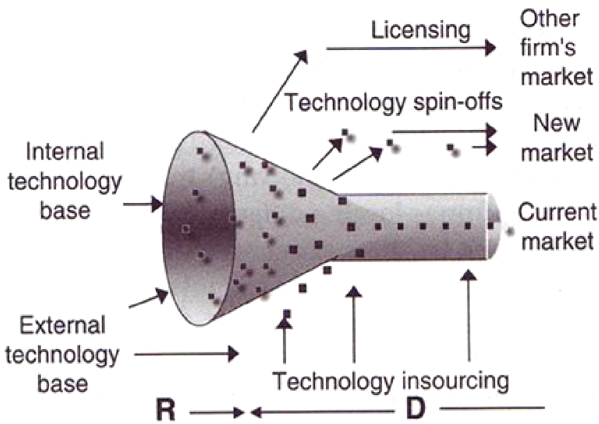

Fig. 5. Open Innovation Process Model [13]

and conference organizers, there are new methods and technologies needed to tap and manage these valuable innovation inputs. By applying these methods for open innovation a firm can overcome its local search bias and acquire precisely the needed information and therefore innovate more successfully and cost efficiently [17]. Main methods used to implement open innovation are:

Lead user method. This method was first developed by Eric von Hippel, who came up with the User/Customer-Driven Innovation paradigm [23]. Von Hippel observed already in the 1980s that the origin of many products and services lays in identifying advanced users – lead users – rather than companies, at the site of implementation and use. Therefore users play a more active and important role than theory had suggested before. Using the lead user method this theory can be applied for improving the innovation output by identifying innovative users and then integrating them by means of innovation workshops. The lead user method also is a proven practice to gather innovative (technological) solutions and so called "need information" which represents the user's experience and requirements [17].

Toolkits for open innovation. These tools are Internet based instruments that aim at supporting users in transferring their needs into new product concepts [17]. Toolkits for user innovation and design are integrated sets of product design, prototyping, and design-testing tools developed to be used by end customers [23]. The goal of a toolkit is to enable non-specialist users to design high-quality, producible custom products that exactly match their requirements. Toolkits often contain "user-friendly" features that guide users at their effort. However, they are restricted to a type of product or service and a specific production system. There are a growing number of firms using these toolkits to address individual requirements substituting market research via direct user-interaction [10]. For example, a toolkit provided to customers interested in designing their own, custom digital semiconductor chips is tailored precisely for that purpose – it cannot be used to design other types of products [23]. Users apply a toolkit in conjunction with their rich understanding of their own needs to create a preliminary design, simulate or prototype it, evaluate its functioning in their own use environment, and then iteratively improve it until the design satisfies the particular user need.

Innovation contests. Those contests aim at the generation of input for all stages of the innovation process [17]. In an innovation contest, a company calls on its customers, users, or experts in the general public either to disclose innovative ideas and suggestions for product improvement, or it asks for a very specific solution for a dedicated (technical) innovative task. The contests come in different types. They can be a very broad call for contributions directed at all (potential) customers of the company and/or a very dedicated question to a smaller team of specialists in a specific community. Idea contests can serve to integrate customers, or users typically aim at encouraging innovative ideas at the front end of the innovation process. However, innovation contests can also begin in a later stage in the innovation process; usually in searches for innovative approaches to a technical problem within a broad field of problem solvers. These contests go beyond the user innovation perspective and address the ideas of crowdsourcing when tasks which were traditionally performed by an employee or contractor are outsourced to a group of people or community, through an "open call" to a large group of people (a so called crowd) asking for contributions [13]. Not only at this point Open Innovation and Web2.0 ideas start to overlap significantly. To facilitate these contests, contest organizers are needed to formulate the problem, lay down the rules for participation, usually collects the contributions, evaluates them, and then chooses the winner. Companies have already specialized in acting as an intermediary by organizing idea contests for other organizations. Examples include firms like Hyve AG or Idea Crossing. Typically, these intermediaries are called Open Innovation Accelerators (OIA) [17]. However, idea competitions can also take place within a firm following the EDI/Closed Innovation paradigm typically for traditional CAI. Today, many firms have an intranet portal on which employees can submit their ideas and suggestions for improvement like IBM and their “Innovation Jams” [24]. IBM was so successful internally with this solution that the company now sells the “Jam” idea as a consulting service to other companies becoming a contest organizer.

Stage 4: Flexible NPD System & FFE-OI. The old model inspired by Cooper [18, 19] exclusively focused on the closed innovation perspective with a strong market and customer orientation but not customer or other stakeholder integration. Therefore, the next evolutionary step in this model should be the introduction of open innovation methods in the NPD capabilities of the next maturity stage. As most firms will use their established close innovation NPD-processes in parallel, Stage 3 is complemented by open innovation methods especially in the fuzzy front end of the innovation process (FFE) and in this way develops the fourth generation: Flexible NPD System with FFE-OI-Methods.

Stage 5: Holistic NPD System. To forecast the future stages in the dominant logic of the NPD-CAI-Systems Maturity Model would suggest that both approaches (Closed Innovation NPD-systems and Open Innovation approaches) unite into a unified fifth generation Holistic NPD System in which OI-methods and EDI would be united in a complementary manor. The future NPD system of firms would combine and integrate internal and external communities for the entire innovation process. However, also another scenario could be constructed in which Closed Innovation and hierarchical organized firms will be completely substituted by innovation networks and peer to peer platforms totally based on crowdsourcing, folksonomy and Open Innovation methods going far beyond by Enterprise 2.0 concepts [13, 16, 25]. Nevertheless, the CAI-NPD-Systems Maturity Model would not be suited to be a good theoretical framework for explaining such a radical shift as it assumes a gradual improvement along the maturity and supporting capability dimensions.

3.2 New CAI Maturity Stages Based on Web 2.0

In order to support the various methods resulting from the Open and User Innovation Paradigm specific IT-solutions are increasingly developed to enable firm-external participants to integrate more directly in the innovation process [17]. This development expands the traditional CAI-concept towards the Open Innovation sphere. In parallel to the developments in the area of innovation management and theory described in the chapter above parallel progress took place in the area of software which is relevant to the area of CAI. The latter development is frequently described by the term Web 2.0. This terminology lacks a clear definition so far and many discussions about its real content and its future development to Web 3.0 are on-going [8, 9]. Nevertheless certain web technology developments in the last 10 years lead to a new breed of web services that have certain elements in common that build the core web 2.0 elements. These core elements are cloud computing, desktop-like usability, interactivity and the semantic web, which are relevant also for the emerging of Open CAI 2.0. These elements and their influence on CAI will be explained in the following:

Cloud computing. Cloud computing is defined as software architecture in which the central software resides not at the location of the user but in the cloud, which typically consists out of one or more central server systems [11]. Cloud computing offers two advantages that are relevant to the evolution of CAI. Cloud services can be accessed easily by users via a network without the need of any installation (=Software as a Service). And cloud computing allows for an easy scalability of the service. This architecture therefore is the prerequisite to allow not only a pre-defined set of users to use and access the CAI infrastructure of a company, but easily grant access to a nearly endless number of users like BMW is doing with its virtual innovation agency.[1] Cloud computing was also a prerequisite to create open innovation platforms that offer every internet user to participate in many different innovation contests of various companies at the same time, such as Atizo[2] or Brainfloor.com[3] are doing.

[1] http://www.bmwgroup.com/via/
[2] https://www.atizo.com/
[3] http://www.brainfloor.com/

Desktop-like usability. The combination of new web technologies like RSS (Really Simple Syndication), XML (eXtensible Markup Language), JavaScript and others that can be summarized under the term "Ajax" (=Asynchronous JavaScript and XML) allow programmers to develop software that offers rich user interfaces and PC-equivalent interactivity and therefore can be used almost like desktop software despite the fact that it is based on a cloud infrastructure [8]. Those Ajax technologies constitute the basis for easy to use interfaces for untrained users to access CAI tools. While Web 1.0 allowed easy access to information to almost all internet users, Ajax allows these users not only to access information, but also to easily create and share information via the web. For innovation contests it is now possible for users to upload drawings, images and other documents to the idea database without any problems.

Interactivity. Based on Ajax as well as RSS technology the web became much more dynamic and interactive. RSS helps users to receive automatic updates on latest changes, Ajax makes it easy to access and to generate information, and both lead therefore to a much more interactive user behavior. Innovation contests therefore do not only mean to collect ideas from outside, but to discuss and thus enrich those ideas during the process. Discussions about the submitted ideas, even idea evaluations by the users based on ratings or even elements of stock-market trading (e.g. offered by the US software company Spigit) are possible because of these interactive possibilities.

Semantic web. The semantic web refers to the new possibilities to create meta-information. [12]. To a certain extent such information can be automatically created, or is created by the many users. Independent from the source of the meta information, this meta information helps to use and process the loads of information created in the Web 2.0. In the context of CAI meta information can e.g. help to cluster ideas in certain categories, it can help to evaluate ideas and extract ideas that were most heavily discussed or ranked best by the users.

These core technologies helped to create from a mainly one-directional web 1.0, which was focused on spreading information from one central source to many different receivers, a web 2.0 that can be characterized by participation of many users, that relies on the collective wisdom of the crowd rather than a single source, that spread from the PC as the predominant device to a platform and device independent architecture, and that is easily to scale. All those changes are being reflected in the latest developments that can be observed in the CAI world. Software applications predominantly are being migrated to central servers in order to allow a broader user base to access them. Usage of idea management systems becomes more interactive and many more ideas and additional information are being generated than in the past. As an example IBM's Idea Jam can be seen. Over a time period of only 90 hours the 2008 edition created over 32,000 posts from participants from over 1,000 companies. [24] Another example is Dell's idea storm that has lead to over 13,000 ideas so far[4]. By looking at the sheer size of these numbers one can imagine that having ideas is not the crucial issue anymore, but being able to a) identify and motivate the relevant users

[4] http://www.ideastorm.com/

to participate b) generate and/or collect the relevant ideas and c) sort and analyze the received ideas in an effective way.

Open Innovation Accelerators (OIA). Several start-up companies realized these needs and built their business model around this proposition like the mentioned “Open Innovation Accelerators (OIA)”. Based on the newly available web 2.0 technologies and the new open innovation methods several companies started to offer mainly web-based services that offered established companies to utilize the wisdom of the crowd in a relatively easy way in order to increase the efficiency and effectiveness of their innovation process. All those software and service providers can be called OIA and defined as providers of platforms that offer companies the possibility to innovate in cooperation with external actors from the periphery [17]. OIAs typically offer one or several methods of open innovation and, partly, supporting and complementary services for the innovation process. These methods (e.g. lead user, idea contest, toolkit, etc.) are especially focused on the integration of external actors. In consequence, OIAs facilitate a new form of collaboration between an innovating company and its environment. By doing so, OIAs accelerate a company’s internal innovation process.

Open CAI 2.0. Summing up, to integrate these new drivers a new concept, called “*Open CAI 2.0,*” was developed. Open CAI 2.0 is proposed as the next evolutionary step in the CAI development trajectory. As pointed out before, Open CAI 2.0 is based on the Web 2.0-paradigm as well as on the OI paradigm. As shown above, new players like OIAs are entering in the CAI-supplier-domain using these core drivers to establish new CAI-based services to support the innovation value chain. Therefore, Open CAI 2.0 can be defined as category of CAI-tools that use technologies following the Web 2.0-paradigm like Cloud computing, desktop-like usability, interactivity and the semantic web to facilitate OI methods such as Lead user, Toolkits and Innovation contests to open the access of organizations to a larger audience of external actors and enable them to interact in different activities of the innovation process. This evolution is also enforced by Open CAI 2.0 tools which support the OI-methods on an outsourced (using one of the OIAs) or self-managed and developed manner (e.g. IBM’s innovation jam) especially to support the front-end of the innovation process.

Stage 4: Enterprise CAI 1.0 Solutions & Open CAI 2.0. As a result, the Stage 4 of the CAI maturity consists of Enterprise CAI Solutions complemented by Open CAI 2.0 tools provided by OIA or self-developed solutions. The traditional Closed CAI 1.0 tools further serve to support the internal innovation process while the Open CAI 2.0 tools typically support the front-end of the innovation process.

Stage 5: Holistic CAI 2.0 Solutions. This development will also be reflected in Stage 5 with Holistic CAI 2.0 Solutions in which Web2.0 technologies as well as integrated internal and external communities are fully incorporated in the firm’s open and holistic internal innovation process. A seamless transition over firm and communities boundaries will be enabled by future CAI systems to optimize the full innovation process.

Figure 6 provides the updated CAI-NPD-Systems Maturity Model.

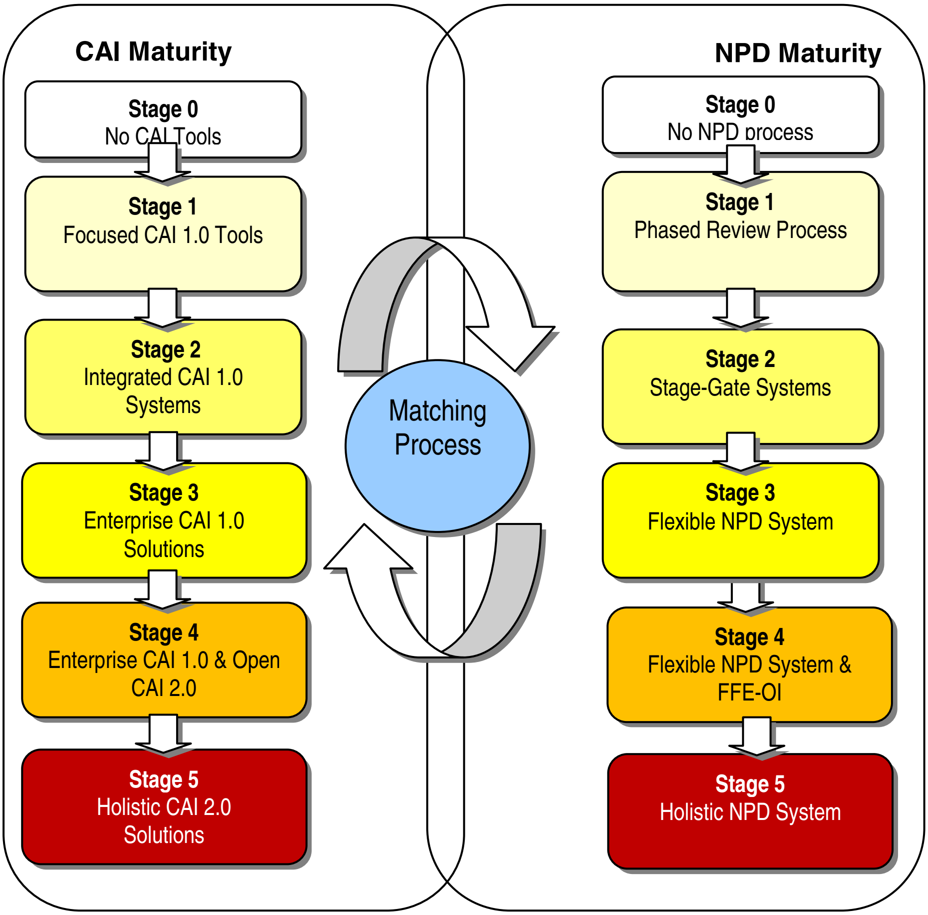

Fig. 6. The updated CAI-NPD-Systems Maturity Model

4 Implications and Outlook

In this section a summary of the presented findings is provided and the implications of this research for users, new and old CAI-suppliers are highlighted. This paper shows how the next generations of CAI could look like based on an updated version of the CAI-NPD-Systems Maturity Model by Waldmannstetter and Hüsig [6] or Hüsig and Kohn [3]. Current and next generations of CAI are influenced by technological developments around Web 2.0, which opened the CAI pipeline management software to a broader user base and therefore even for untrained users. At the same time, the Open Innovation paradigm shifted the attention of companies from employees as main suppliers of new ideas to customers and other users outside the company. Both drivers were mutually dependent and amplified each other and therefore led to an enormous increase of potential users and, consequently, to ideas entering the NPD process in established companies. So far, the processes for these developments have not been aligned with the existing NPD processes but are handled as separate projects. The integration of Open Innovation activities with the internal NPD system and the development of holistic CAI 2.0 solutions will be major tasks for the companies involved.

For new and old CAI-suppliers the roadmap to Holistic CAI 2.0 Solutions contains likewise opportunities and threats. For traditional CAI 1.0 suppliers it is vital to master the transition to Web2.0 technologies and add Open Innovation methods to their existing products to enable Holistic CAI 2.0 Solutions for their clients in the long run. If they fail to deliver this additional functionality, OIA have the opportunity to address this gap and expand their services and technologies into the traditional domain of CAI 1.0 coming largely from the outside and addressing the FFE. The complementary nature for the development trajectory also offers a cooperative solution in which both, new and old CAI-suppliers could unite their particular capabilities to realize Holistic CAI 2.0 Solutions.

However, also an alternative scenario could be constructed in which Closed Innovation and hierarchical organized firms will be completely substituted by innovation networks and peer to peer platforms totally based on crowdsourcing, folksonomy and Open Innovation methods going far beyond by Enterprise 2.0 concepts [13, 16, 25]. Nevertheless, the CAI-NPD-Systems Maturity Model would not be suited to be a good theoretical framework for explaining such a radical shift as it assumes a gradual improvement along the maturity and supporting capability dimensions. This limits the proposed approach and should be analyzed by using different frameworks based on theories like S-Curve or Disruptive Innovation in which the initial worse supporting capability of Web2.0 based CAI approaches as web applications and the less trained user base can be considered more [26].

Future research should focus on the further development of such concepts and solutions outlined in this paper. In particular, more empirical based inquiries are needed if and how the proposed relationships of the updated CAI-NPD-Systems Maturity Model can be supported or alternative approaches are a more fruitful avenue for research.

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CAI for Minimizing Movement of Solar Tracking Concentrators

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Abstract. Computer-Aided Innovation (CAI) has proven useful for creative problem solving, particularly when faced with opposing restrictions. The work presented is faced with such restrictions in terms of solar tracking concentrators. The targeted low cost regarding the tracking system is opposed to the need of a constant precise and controlled movement. The literature revised will be discussed and then areas of opportunity found. The proposal involved the use of computer simulation for concept selection and validation trough a ray-trace method and mathematical models interrelationship for minimizing movement of a solar tracking concentrator. Trace Pro software from Lambda Research is used for ray-trace simulation. This method consists on the projection of a large number of rays over the optical system, and even by reflection or refraction, system's efficiency can be determined. In the end, an optimal solution is found depending on the conditions considered and conceptual designs are proposed.

Keywords: CAI, ray-trace method, iteration, solar tracking concentrator, DE system, semi-passive movement, blind system.

1 Introduction

In this paper, a situation having opposing restrictions is presented in terms of a solar tracking system for solar radiation concentration. A solar concentrating system consists mainly of an absorber, a receiver and a sun tracker. The absorber, which is usually a parabolic dish, has to track to the sun position throughout the day, and even throughout the year. Moreover, the initial position of the tracking system should be calibrated to the particular position on the Earth's surface due to latitude variation. One of the main problems related with the re-positioning of the concentrating system is the weight. The absorber and receiver can sometimes weight over 1,000 kilograms, depending on the size of the dish, the supporting structure and the amount of material contained in the receiver that needs to be heated.

The function of a tracking system is to enable the solar radiation to be concentrated in a limited and well-defined receiver's area. The concentration raises the temperature and the thermal energy may be stored and or transformed to other types of energy. The solar radiation concentration system should consume as little energy as possible for solar tracking.

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Nomenclature	
Aa	absorber area (m^2)
Ar	receiver area (m^2)
a_0, a_1, k	dimensionless constants
β	solar zenith angle
C	concentration ratio
C_e.	effective concentration ratio
C_1, C_2, C_3	variables that allows the calculation of γ
F	furnace factor
H	monthly average solar radiation (J/m^2)
H_0	local average extraterrestrial radiation (J/m^2)
I_{dir}	terrestrial solar irradiance (W/m^2)
I_{ext}	extraterrestrial solar irradiance (W/m^2)
I_{sc}	solar constant (W/m^2)
n	day number of the year
S	monthly average hours of sunlight
S_0	monthly average day duration (hours)
T_r	receiver temperature (K)
φ	earth latitude
δ	earth declination
τ_{dir}	atmospheric transmittance (%)
σ	Stefan-Boltzman constant (W/m^2K^4)
ω	angular displacement of the sun to east or west with respect to the local meridian
γ	solar azimuth angle
γ’	pseudo solar azimuth angle

For achieving a low cost tracking system the following contradiction has to be solved: on one hand the solar tracking system has to follow the sun movement. On the other hand, it is desired that the system does not move in order to not require the use of energy and therefore to minimize cost. The reconciliation of these opposing requirements has been understood as a problem that needs an innovative perspective.

The literature shows efforts that have been mainly directed to find more refined algorithms and sensing methods for tracking the solar movement. However, only limited attention has been paid to the rest of the tracking system (i.e. the structure, the materials used, and the architecture of the object). We have found only few, yet useful, works aimed to find ways to reduce the need to move on Gottsche et al., 2005 [12]; Kribus and Ries, 2002 [15].

1.1 CAI

The work presented at this paper follows an approach of Computer-Aided Innovation (CAI), which has proven useful for creative problem solving particularly when faced with opposing restrictions, such as the ones established above. It aims at the optimization of solar tracking systems by minimization of active movement, but taking cost requirements as also the amount of energy collected in account. A method for solving the problem is presented that enables the exploration of innovative solutions aided by computational tools. These latter have facilitated the expansion of creative exploration, the global interdependence of the system's components, and the simulation of different scenarios. Without the aid of computers, calculations and modeling would have taken longer periods of time, limiting the amount of ideas that can be tested as well as the time dedicated to imagine creative alternatives, therefore it may be claimed that a computer-aided innovation process has been applied. The contributions include but are not limited to: problem analysis acceleration and solution exploration enhancement.

Computer aid has gradually permeated the whole product design and development cycle. From the initial Computer-aided Design (CAD) and Computer-aided Engineering (CAE), the exploitation of machine calculation power has extended to the realms of innovation. Computer-aided Innovation aims at helping in tackling the problems related with innovations failures. According to Dorr et al., CAI is not limited to the use of personal computers within the innovation process, or the use of innovation tools such as TRIZ in computerized environments. It is rather the adoption of advanced information and communication methods and tools aimed at integration, virtualization, multi-scalable and multicultural collaboration [9]. The intention of these tools is to support the creative phases of design in various meaningful ways. One of them is helping the designer to model different ideas in a virtual environment and in relatively short periods (as opposed to the manufacturing of prototypes for each new idea imagined). This results in important reductions in costs in the conceptual phases of product design. Another advantage that has lately been valued is the possibility of creating new options in ways that weren't imagined before. According to Albers et al., computational tools can help in the generation of new solutions emerging from many disconnected ideas, and suggesting new concepts [4].

The present work explores this realm and presents the results of an innovation process that has been accompanied by computer simulation and optimization. The document that follows is organized in third main sections. The first one explains the generalities of a solar tracking system and the problems its design presents. It also contains a review of works done lately in terms of those problems and where areas of opportunity still lie. The second section includes our proposal, both method and application. The third one establishes the results obtained, what it can be concluded from them, as well as the achieved contributions.

2 Solar Tracking Concentrators Generalities

A solar concentrating system consists mainly of an absorber, a receiver and a sun tracker. The absorber, which is usually a parabolic dish, has to track to the sun position throughout the day, and even throughout the year. Moreover, the initial position of the tracking system should be calibrated to the particular position on the Earth's surface due to latitude variation.

There are two main types of concentrators: two-dimensional, and three-dimensional. The former concentrates the solar energy throughout a line, while the latter does it in a spot. The present work considers for the case study the architecture of the type of solar concentration system called Dish/Motor (DE) shown in Fig. 1.

In terms of the overall architecture of the system, patents found in [7], [8], [11], [13], [17], [18] and [19] can attest for the attempts of reducing or eliminating the need to adjust the system to the Sun's position. Nevertheless, a tracking system that can chase the sun rays to obtain heat is ultimately indispensable. Studies for that particular part of the system can be found in [1], [2], [3], [4], [5] and [6]. The literature has as common denominator: the optimization of the system through a reduction of the periodic movement or else through an improvement of the electro-mechanical systems that enable an appropriate orientation. Up until now, however, no concentration system has eliminated the adjustments needed to compensate the variability in the solar trajectory. As much as it can be reduced, it nevertheless impacts in a direct way in the temperatures achieved and thus the overall efficiency of the system. This works aims at the exploration of innovative ways to tackle this issue.

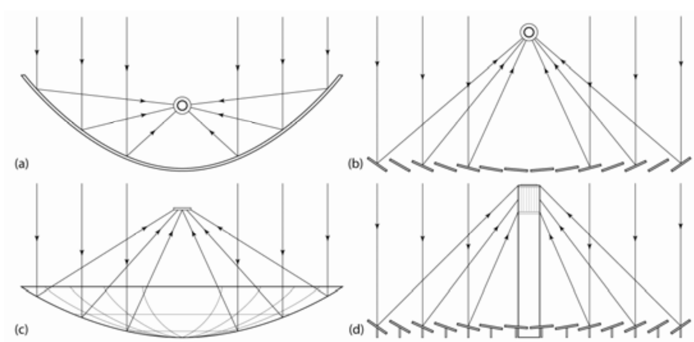

Fig. 1. Solar concentration systems. Linear concentrator (a) PTC / (b) LF, and spot concentrator (c) DE / (d) CRS

3 Proposal

The work presented at this paper aims at the optimization of solar tracking systems by minimization of active movement, but taking cost requirements as also the amount of temperature collected in account. A method for solving the problem is presented that enables the exploration of innovative solutions aided by computational tools.

The methodology used in this paper consists in the interrelationship of a ray-trace method and mathematical models. This allows the evaluation of different scenarios in a short period of time without costly prototype iterations. TracePro is used for ray-trace simulation, a method that consists on a projection of a large number of rays over the solar concentrator system. Mathematical models are interrelated trough spreadsheet software. These permit the performance calculation of the simulated concepts, in particular, the temperature on the receiver as this is the essential part of the concentrator's efficiency. If results are not satisfactory, iteration takes place and returns to the simulation stage. Once a scenario has been selected as a function of its movement reduction and temperature, concept is improved until results can't get better with the established system's configuration. During validation stage, physical testing is performed trough a solar concentrator scale prototype.

Mathematical models that relate solar energy variables are firstly explained. Then conceptual designs and their evaluation are presented to finally conclude with the optimization of the selected system for further validation.

3.1 Mathematical Models

The mathematical models allow the calculation of the main parameters of the solar concentrator system performance. These permits to visualize the behavior of different solution alternatives under ideal conditions in a short period of time such as solar motion variables, incident radiation and concentration temperature.

Since the main focus of this research is the use of CAI tools for problem solving, mathematical details are omitted and only a brief general idea of the formulas are described on the nomenclature table at the beginning of the paper. For further description of all the mathematical variables it is suggested a literature review presented in [6], [10], [14] and [16].

The apparent solar motion is one of the main variables to consider when designing a solar concentrator. Duffie and William [10] propose the following expressions to describe the sun's path

$$\cos\beta = \cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta. \tag{1}$$

$$\delta = 23.45\sin[360(284 + n/365)]. \tag{2}$$

$$\gamma = C_1C_2\gamma' + C_3(1 - C_1C_2/2)180. \tag{3}$$

The performance of any solar system not only depends on the solar tracking, but also in the amount of radiation available on Earth, thus the equations to calculate this variable are set according to Bakirci, 1961 [6]; Hottel, 1976 [14]; Liu y Jordan, 1960 [16].

$$H/H_0 = 0.23 + 0.48(S/S_0). \quad (4)$$

$$I_{ext} = I_{sc}[1 + 0.033\cos(360n/365)]\cos\beta. \quad (5)$$

$$\tau_{dir} = a_0 + a_1\exp(- k/\cos\beta). \quad (6)$$

$$I_{dir} = I_{ext}\,\tau_{dir}. \quad (7)$$

Yet another variable involved is the relationship between the absorber's area and the receiver's area. The higher the ratio the higher the system's temperature. However, an *F* variable decreases that concentration ratio due to heat losses and converts it to C_e. With this information it can be determine the temperature achieved by the concentrator. These variables are expressed through the following equations

$$C = A_a/A_r. \quad \mathbf{(8)}$$

$$C_e = FC. \quad \mathbf{(9)}$$

$$T_r = \sqrt[4]{(C_e I_{dir}/\sigma)}. \quad \mathbf{(10)}$$

Notably, the case of study of the present research focuses on the installation of the system on a latitude φ = 25°39'15''N, which corresponds to the city of Monterrey, N.L., México. The solar path and amount of radiation at this particular location allows the calculation of the temperature achieved by each concept in order to select the one that will need further validation.

3.2 Computer Simulation by Ray-Trace Method

In this section all the solar concentrator's concepts are shown. From each one of them we obtain the T_r values using the mathematical models previously described.

The use of a computer tool to support the reduction of *DE system* movement due to solar position variability is the main objective of this stage. The functional analysis of DE technology involves the relationship between absorber and receiver, solar tracking system and support structure. If we require minimizing the solar concentrator movement, is therefore necessary to consider a separate system that compensate the sun's path and redirects its radiation perpendicular to the absorber's surface. Therefore *Concept A* is proposed. In this concept, a series of reflective surfaces in a blind arrangement are placed above the concentrator. Each blind has a size of 0.1m × 0.5m, thus 19 flat surfaces are required to cover a 1m^2 absorber's area as shown in Fig. 2.

On one hand, having a stationary *DE system* requires less engine power for sun tracking. On the other hand, blind configuration generates shadows between each pair of reflective surface in low solar angles. Each blind blocks certain amount of radiation to its nearest neighbor, so the amount of power sent to the dish surface and temperature decreases. To avoid this, the tracking system must be tilted properly depending on φ.

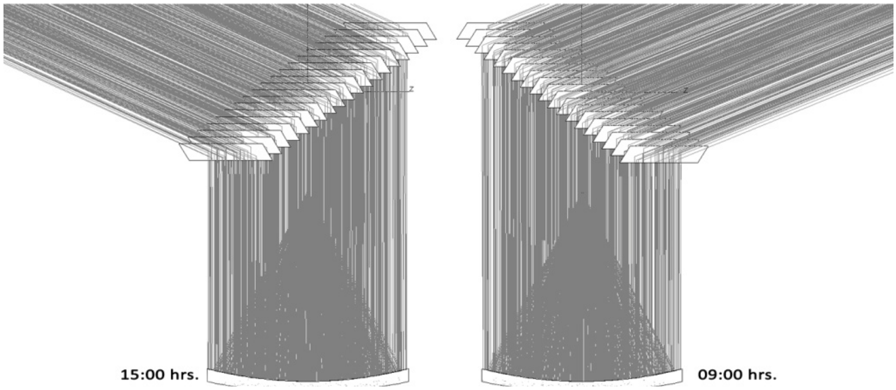

Fig. 2. Concept A

A design consideration of the tracking system is the space required for its movement. If it is desired to install the tracker on the roof of a house, it is necessary to remain the blind's framework stationary. From this perspective, *Concept B* divides each blind into three equal segments as shown in Fig. 3. The parabolic dish and receiver remain stationary on the horizontal plane. Despite being a semi-stationary concentrator, blind segments complicate the electro-mechanical system and increase its cost. Despite this, the system has the highest amount of solar radiation collected only at noon as it covers the entire absorber's area, while in the morning and afternoon the concentrated energy decreases due to blind segments separation.

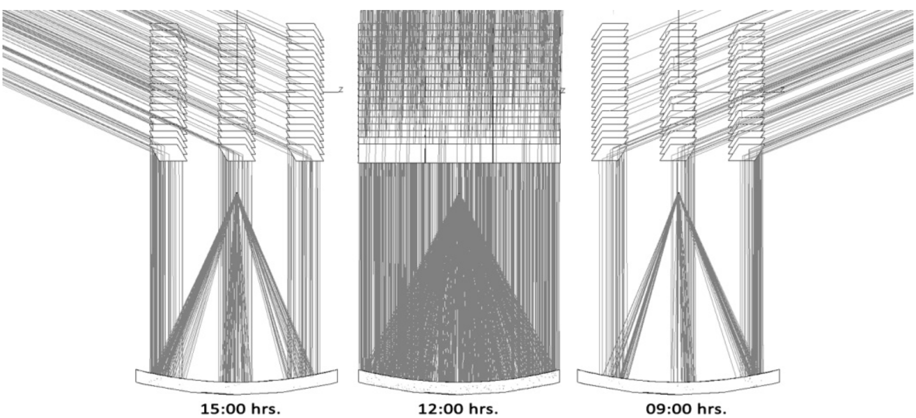

Fig. 3. Concept B

Concept C showed in Fig. 4 take some of the best features of previous solutions. The system consists of a series of blinds split in half that minimize tracking while the blind's structure remain stationary and the number of components minimized. Due to absorber's orientation, the incident radiation at noon maximizes T_r since the whole dish's area is used. The absorber and receiver must be minimally shifted throughout the year.

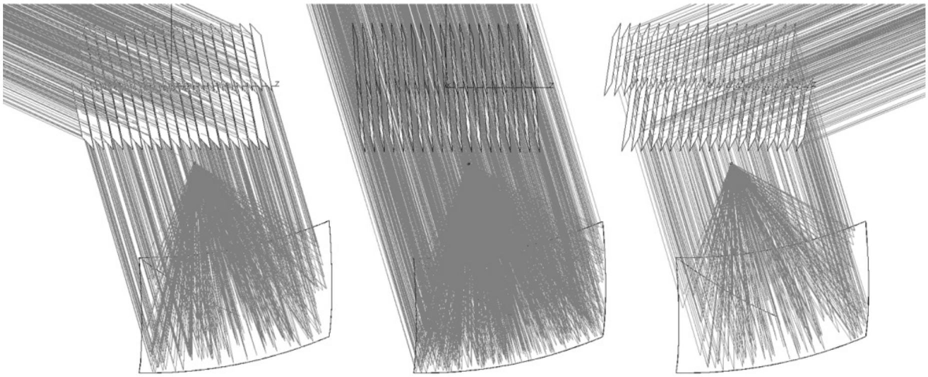

Fig. 4. Concept C

3.3 Evaluation

The evaluation of previous scenarios requires computational tools to measure the motion reduction in both azimuth and altitude angles (see Table 1) and the temperature profile (see Fig. 5). Both results allow the selection of an adequate concept for further improvement.

In order to measure the *DE system* movement's reduction, the solar angles β and γ were taken as the basis to determine the variability of the position of the each concept blinds.

Table 1. Two-axis motion made by DE system and all design concepts from 9:00 to 15:00 hrs

Concept	Altitude	Azimuth
DE	24º	70º
A	13º	70º
B	32º	70º
C	35º	10º

The *DE system* requires a two axes movement to compensate the solar angles variation and concentrate radiation on the receiver. It takes 24º in altitude and 70º in azimuth to achieve it, which could be difficult depending on its weight. Despite this, the system reaches the highest temperature levels comparing to other types of concentrators. By using 1m^2 with a C_e=1000, it is possible to achieve a temperature of 1484ºC at noon on φ=25º39'15"N.

Concept A shows a 54% decrease in altitude movement and remains constant on azimuth compared to *DE system*. Despite this, blinds must have enough space to achieve this motion as their configuration suggests the reorientation of its whole structure. The temperature profile is affected at noon due to shadow generation between blinds.

The motion carried by the *DE system* increases in *Concept B*. However, these latter requires a stationary dish and receiver, thus eliminating majors efforts for sun tracking. Finally, *Concept C* shows a 46% increase of movement in altitude and a decrease of 86% in azimuth compared to *DE system*. Beside this, the temperature profile has a value of 1484ºC at noon on May and July, which equals the maximum temperature of the *DE system*. It is therefore appropriate to think that *Concept C* is ideal for solving the research problem; however, it requires design improvement in order to raise the temperature profile around noon.

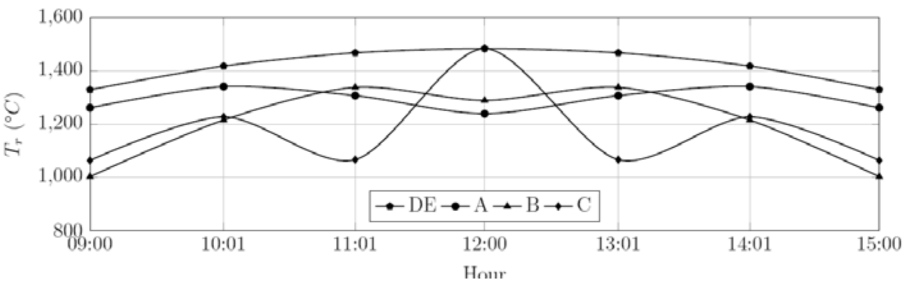

Fig. 5. T_r reached by all design concepts on May/July (maximum T_r)

3.4 Concept Improvement

This section discusses the conceptual improvement process for *Concept C* previously selected following a CAI approach. The main objective is to collect the maximum amount of solar radiation around noon to maximize the temperature reached by the system. Low temperature profile is due to decrease of the blinds visible area with respect to the sun around noon, which reduces the effective area of the absorber and thus the concentration ratio.

A possible solution is to increase the visible blinds surface at noon; which means increasing its quantity inside a 1m^2 area. Finding the optimal dimensions and blinds spacing requires a certain iteration to achieve improved results; ray-tracer software and mathematical models are useful tools to determine quantitatively the optimum problem solution. Different blind dimensions and spacing were simulated. T_r values achieved by these options are shown in Fig. 6.

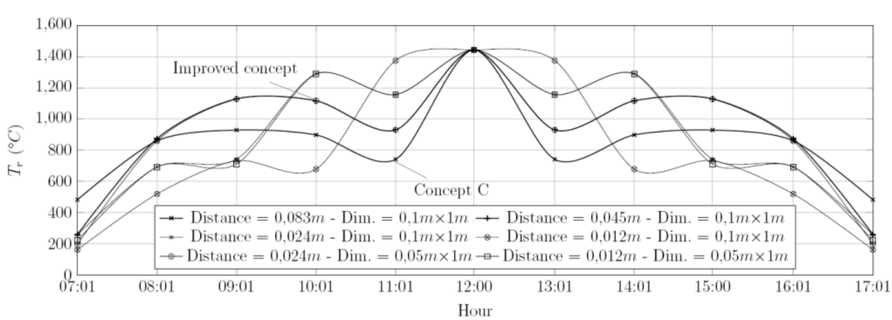

Fig. 6. T_r reached on May/July with different distances and dimensions of solar blinds within an area of 1m^2

Concepts with the greatest temperature stability are the ones with blind separation of 0.045m and 0.05m with dimensions of 0.1m × 1.0m and 0.05m × 1.0m respectively. The former requires 42 blinds, while the latter 82. Both concepts have an average temperature increment of 250ºC from 9:00 to 15:00 hrs. with respect to the original one.

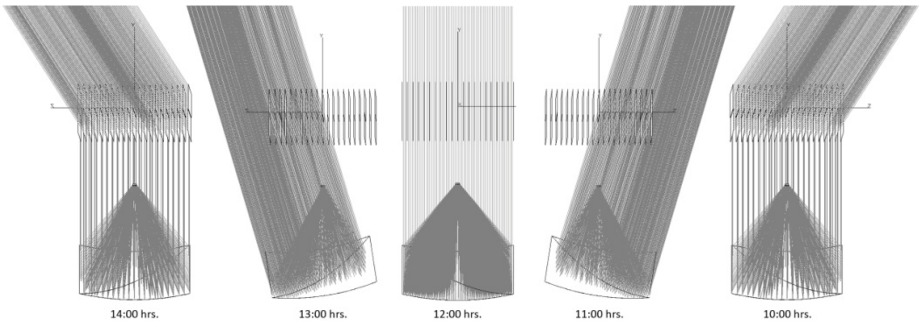

Fig. 7. Solar concentrator system with blind system and minimum movement dish

Although T_r shows an increment with the system optimization achieved so far, there are temperature valleys at 11:00 and 13:00 hrs. On one hand, *DE systems* generate a constant temperature profile because they remained the perpendicularity between the dish's surface and the solar radiation throughout the day; however, periodical movement is required to do so. On the other hand, minimum tracking suggest the usage of blinds to eliminate this adjustment. Therefore, using this latter at mornings and evenings combined with a semi-passive dish at noon, the objective of T_r maximizing can be accomplished (see Fig. 7). A temperature comparison between fixed and semi-passive absorber is shown on Fig. 8.

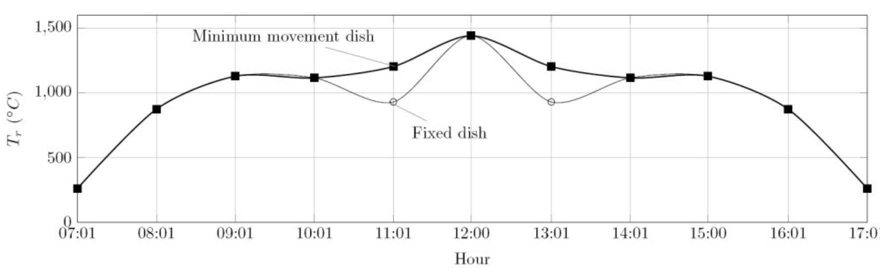

Fig. 8. T_r reached by a semi-passive solar concentrator on March/September

3.5 Validation

The objective of this section is to validate the performance of the solar concentration system trough physical experimentation. For that reason, a $1m^2$ scale prototype was build and proved.

The validation stage allows verifying the simulated performance of the improved system through a prototype that resembles its operation.

The computer simulation allowed the visualization of the concept's behavior under "virtual conditions", however, some other aspects as assembly, weight, movement, and other problems arise when taking the system to real life. Besides this, it is possible to obtain tangible results by taking into account some variables unconsidered before as a calculated solar angles precision, real incident radiation and final concentration temperature due to heat losses.

A $1m^2$ prototype was build because its results can be replicated when scaling as long as concentration ratio remains constant. Because it is pretended to build a $30m^2$ system for home electricity generation, the concentrator could be either scaled or repeated.

The prototype comprises an architecture made of a parabolic dish and a blind system both coated with a 95% hemispherical reflection film. Blinds were assembled into three degrees of freedom structure for sun tracking throughout the day and year.. The concentration factor resulted in a ratio of 1:670 due to dish geometry. Prototype's architecture can be seen on Fig. 9.

The parameter that allowed system validation was the temperature T_r obtained by using a high efficiency thermometer. Validation stage took place on φ=25º39'15"N in order to obtained similar results between computational simulation and real conditions operation. This latitude corresponds to Monterrey, N.L., México, which has a solar radiation average of $0.934kW/m^2$ during daytime as shown in Fig. 10,

Fig. 9. Semi-passive solar concentrator prototype

T_r results are shown in Fig. 11. It is observed that the system's temperature profile is similar to the one obtained in the concept improvement stage. In both graphs, T_r valleys are eliminated by moving the dish around noon hours.

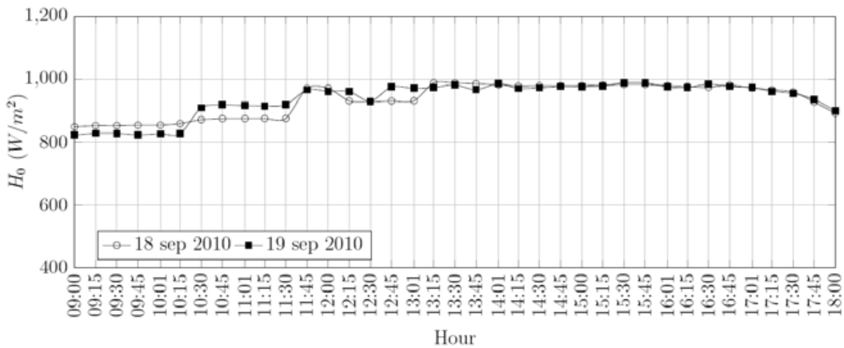

Fig. 10. H_0 on φ=25°39'15"N

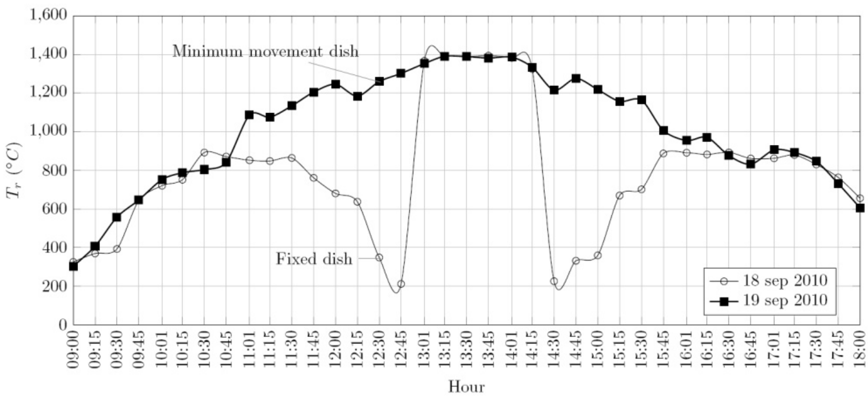

Fig. 11. T_r reached by semi-passive solar concentrator prototype

4 Results and Contributions

This research solved the resultant contradictions through a CAI approach by means of computational tools that helped to reduce DE concentrator movement required to follow sun's path. Optimal results were obtained by iteration method that related ray-trace tool with mathematical models. On one hand the ray-tracer helped to visualize the different concepts that would lead to the solution. On the other, the results that allowed the concept selection were possible due to calculus software that permitted a quick and precise interrelation between several mathematical variables, making the development a greater number of alternatives possible.

A relationship between CAI and an iteration methodology was proposed. Through a series of steps, this helped to find an optimal solution in a short period of time. The concept simulation was the first step of the research, were different solar concentrators systems were modeled in CAD software and simulated in Trace Pro. Without this tool, the rapid and accurate conceptual exploration performed wouldn't have been possible. The complement of the simulation was the solution of mathematical models with calculus software that allowed the evaluation of temperatures as a function of solar movement and amount of incident radiation. As a case of study, values corresponding to φ=25º39'15"N were used. While the expected results were not achieved in the previous stage, concept improvement allowed adjusting certain parameters under CAI approach. Finally, validation stage allowed the construction of a prototype in order to verify its functionality under real conditions. Although the use of computational tools was omitted at this point, the prototype wouldn't have been possible without a previous virtual simulation and evaluation.

Accordingly, it can be established that CAI approach promotes problem solution in a fast and creative way. Its relationship with an iterative methodology led to the development of a semi-passive solar concentrator in a short period of time and at low cost.

5 Conclusions

A method for solving the problem is presented that enables the exploration of innovative solutions aided by computational tools. These latter have facilitated the expansion of creative exploration, the global interdependence of the system's components, and the simulation of different scenarios. Without the aid of computers, calculations and modeling would have taken longer periods of time, limiting the amount of ideas that can be tested as well the time dedicated to imagine creative alternatives.

Acknowledgments

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Computer Aided Optimization/Innovation of Passive Tracking Solar Concentration Fresnel Lens

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Abstract. A passive solar tracker and concentrator device must be able to effectively concentrate solar radiation into a constant area throughout the day, without any mobile mechanism. The objective is to achieve 1000 °C on the receptor area with concentrated solar energy, and to accomplish this target a compound Fresnel lens has been designed. Utilizing multidisciplinary CAE software, an integrated multi-objective optimization process based on genetic algorithms has been developed and a novel design solution has been achieved. The process consists of integrating genetic algorithms using optimization software Dakota from Sandia National Laboratories with Autodesk Inventor for parametric variation of the lens 3D-CAD geometry, Lambda Research TracePro software for ray tracing simulation, and Microsoft Excel to manage data input and output. Several simulation scenarios were developed, such as a solar tracker and concentrator device for two-dimensional (linear) concentration and three-dimensional (spot) concentration on equatorial and non-equatorial locations.

Keywords: Optimized Fresnel lens, passive solar tracking, genetic algorithms, solar concentrator, computer-aided innovation, solar thermal energy.

1 Introduction

Most solar energy research has focused on photovoltaic (PV) cells, which generate electricity with a molecular chain reaction. This reaction is triggered by a solar energy flux that occurs on a thin layer of silicon or germanium based compound. However, commercial PV cells have only yet achieved a15% to 20% efficiency rate [1].

Two main issues about solar thermal energy must be overcome. First, solar energy must be concentrated for thermal applications, this due the low-density nature of such energy. Second, for most solar concentrators, solar rays must fall perpendicular to the concentrator at all times. Therefore, a solar tracking device must be used. A third factor could be the uncertainty of weather conditions, as not all locations in the world have regularly sunny days during most of year.

This work was done to explore the feasibility of using a Fresnel lens as a solar concentrator and passive solar tracking device. The main objective of this research work is to develop an automated optimization process for a solar tracking and concentrator device that will concentrate solar thermal energy into a thermal tank. Subsequently, the thermal battery (or tank) will be used as a power source for a Stirling engine to produce electricity. A Stirling engine is a machine that transforms

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thermal energy to mechanical energy using a work fluid. Several systems have been developed previously for such propose [2, 3]. Focusing solar rays into a thermal battery instead of focusing them directly to the Stirling engine gives mobility to the system, which is more practical for electric generation applications. Also, it opens the possibility to use thermal stored energy for transportation vehicles.

The developed automated optimization process uses a 3D-CAD modeler, ray-tracing simulation software and a commercial genetic algorithm (GA) package. To understand the simulation parameters and how it works, some basic background information of solar concentration and GA is presented.

1.1 Solar Concentration and Tracking

There are two types of solar concentration linear and spot, where linear or 2D concentration refers to an area concentrated to a line and 3D concentration refers to an area concentrated to a spot. 3D concentration achieves the highest practical concentration level.

Solar irradiance intensity changes depending on geographical location, season of the year, weather conditions and time of day. The Liu, B. & Jordan, R. model [4] was used to describe solar irradiance of Monterrey, Mexico (with a latitude of 25°40´ N).

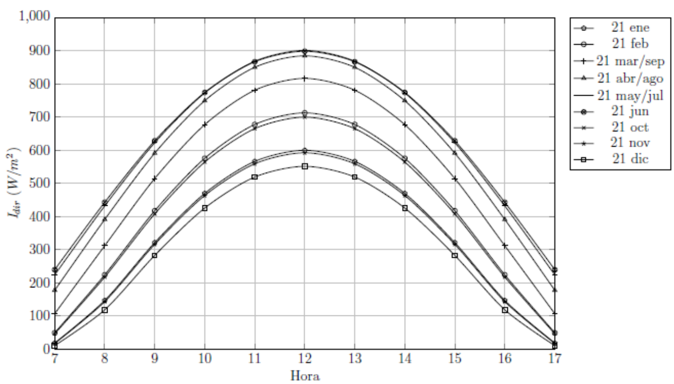

Fig. 1. Direct solar irradiance in *W/m²* (vertical axis) from 7:00 to 17:00 *hours* (horizontal axis) on different dates of the year in Monterrey, Mexico

As you can see, the highest irradiance intensities are between 9:00 hours and 15:00 hours. Thus the solar concentrator and passive tracking device is designed to work during that window of time.

To reach 1000°C on target with solar energy as the only power source is a matter of concentration levels and solar irradiance at a specific moment of the day. The following graph shows the concentration level versus temperature relation, using a basic thermodynamic model [5].

$$T_{r,max} = T_s \sqrt[4]{\frac{C}{C_{max}}}. \tag{1}$$

Where $T_s = 5777\ K$ is the temperature of the Sun's surface.

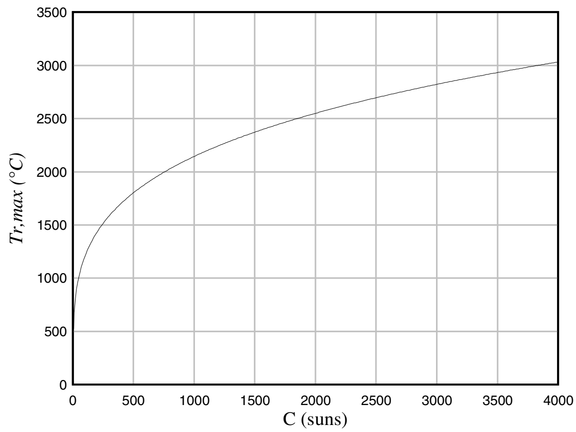

Fig. 2. Maximum thermodynamic temperature in *°C* (vertical axis) relative to the concentration level in *suns* (horizontal axis). No thermal losses were considered in this model [5]

According to the above model, to achieve 1000°C on target (focused area) a minimum concentration level of 100 suns is needed, which is essential for the design parameters of our solar concentration and passive tracking device.

To reach higher levels of solar concentration, typical solar collectors must decrease their acceptance half-angle. Therefore, it is necessary to follow the Sun's apparent movement respective to the Earth. There are different techniques employed depending of the level of concentration needed. Three main categories are listed below [6].

- *Seasonal tracking*
- *Single axis tracking*
- *Double axis or ideal tracking*.

This document presents a device with no movement, using Fresnel lenses to concentrate and to track the Sun´s first axis of apparent trajectory. The second axis of trajectory (or seasonal axis) can be compensated by an inclination of the device towards the south (or to north at the southern hemisphere), where the inclination angle must be the same as the geographical latitude angle of the device´s location (in our case Monterrey is roughly at 25° 40' N) [7].

1.2 Fresnel Lens Exterior Shapes and Internal Prisms

Dome-shaped (3D) or arched (2D) lenses can be designed when the prisms are chained along a semicircle centered at the focal point. A shaped lens offers advantages over flat lenses, such as increased mechanical stability with Fresnel grooves located inside for easy cleaning, and also reduces focal aberrations, but has the disadvantage of a more complex manufacturing process. Other more complex systems integrate closed loop control to change the refraction index of a liquid crystal material located between two layers of Fresnel lens grooves [12, 13]. To construct a

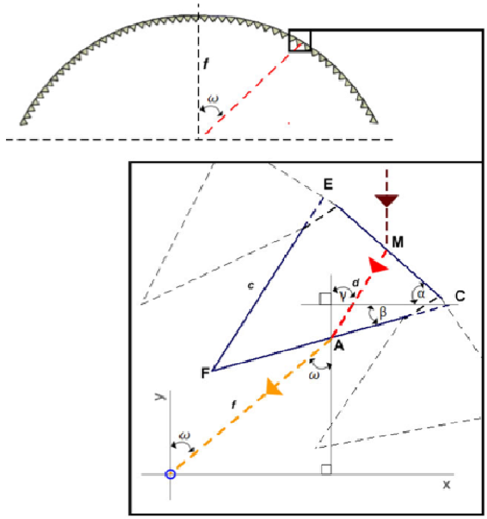

Fig. 3. Shaped Fresnel lens profile diagram [7]

shaped Fresnel lens, first the prism's angles and position must be calculated, as shown in the following diagram:

Based on the parameters depicted in Fig. 3, the following two equations can be set [4]:

$$\sin a = n \sin(a - \gamma) \tag{2}$$

$$n \sin(\beta - \gamma) = \sin(\beta + \omega) \tag{3}$$

Where n is the refraction index of the Fresnel Lens Concentrator (FLC) material. With $a = \omega$, eq. (2) can be solved for γ via:

$$\gamma = \omega - \sin^{-1}\left(\frac{\sin \omega}{n}\right) \tag{4}$$

Using sine theorems eq. (3) is solved for angle β :

$$\beta = \tan^{-1}\left(\frac{n+1}{n-1}\tan\left(\frac{\omega - \gamma}{2}\right)\right) - \frac{\omega + \gamma}{2} \tag{5}$$

With equations (4) and (5), for γ and the prism inclination angle β respectively, the design of the lens can be determined by the fixed focal length f which in turn determines the prism´s angle a (as defined in Fig. 3). Using the above equations, a first shaped Fresnel lens model was drawn in Autodesk Inventor (CAD software) for its future optimization with GA.

Poly methyl methacrylate (PMMA) commonly known as acrylic, is the material chosen for the FLC, has a 1.49 refractive index at 0.587µm and transmits light up to 92% (in a 3mm thick sheet) [7].

1.3 An Ideal Final Result Approach

There are several relevant contradictions that need to be overcome in order to find a best possible solution within the set range of boundaries. However, the most important contradiction is that the solar tracking device must follow the sun's apparent trajectory without any moving mechanism. This is not naturally possible due to the constantly changing angle of the solar rays in relation to the Sun's apparent trajectory throughout the day. Also, the refraction/reflection index is typically a constant material property; therefore, rays with different angles of incidence will be refracted or reflected to different locations. There are solar tracking methods that do not involve power consuming actuators, yet those systems have moving parts and for applications where a large area of absorption is needed (i.e. $30m^2$), a system with moving parts becomes more expensive and less practical in residential locations.

From an ideal final result point of view we understand passive solar tracking as a system that does not involve moving parts, and therefore a "tracking but not tracking" solution is needed. A passive solar tracking and concentration device was idealized as a fixed (movement free) apparatus that concentrates solar energy with a constant focus location for high concentration ratios. A universal geometric shape of a Fresnel lens was developed, where the lens refracts all solar rays towards the same spot no matter the incidence angle of the solar rays. In order to find this universal geometric shape, the use of genetic algorithms was chosen.

1.4 Genetics Algorithms

Genetic algorithms (Gas) are search algorithms based on the mechanics of natural selection and natural genetics. In every generation, a new set of artificial individuals (represented as strings) is created using bits and pieces of the fittest of the previous generation. Gas efficiently exploit historical information to speculate on new search points with expected improved performance.

Genetic algorithms are implemented using computer simulations to reduce the research time of a best suited solution to a specific problem, in which members of a universe of possible solutions, called individuals, are represented by chromosomes. A simple GA that yields good results in many practical problems is composed of three operations: Selection, reproduction and mutation [8].

2 Process Integration Using Dakota and Batch Scripts

Dakota by Sandia National Laboratories is an open source program used to apply GA methods to the optimization problem of a FLC and passive solar tracking device. Dakota handles codification of FLC CAD parameters; however, an exterior process is needed as an objective function to evaluate the created individuals [9]. The exterior process is executed in sequence by a batch file (windows based command line file). The following diagram presents how the developed automated process works:

Once the process´ cycle is completed, an evaluation (fitness) value is assigned to the individual (a set of parameters that conforms to the FLC CAD part). Dakota reads and stores the fitness value and then proceeds to the next iteration.

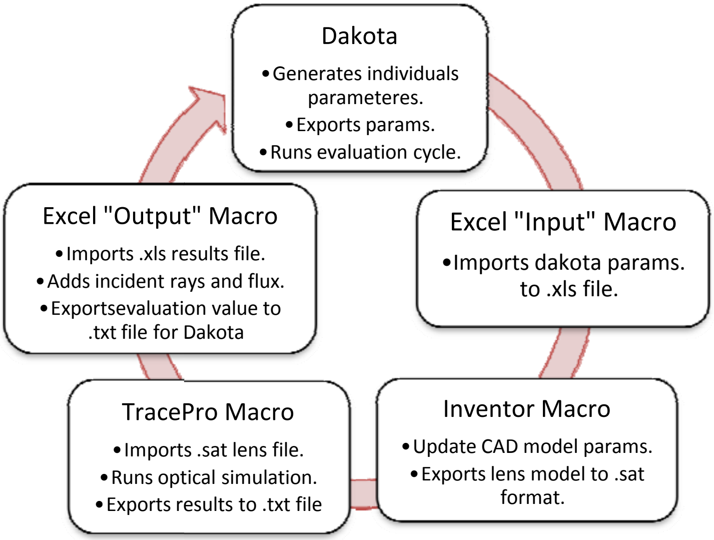

Fig. 4. Descriptive diagram of developed optimization process

Dakota has two commercial GAs optimization methods: Multi-Objective Genetic Algorithm (MOGA) and Single-Objective Genetic Algorithm (SOGA). Both were applied to different optimization scenarios described in the following section.

2.1 FLC CAD Part Parameters

Using section 1.4 equations, a CAD part was drawn and parameterized in Autodesk Inventor 2009 with general dimensions of 0.6m x 0.5m. The next image shows a section of the FLC profile and its parameters.

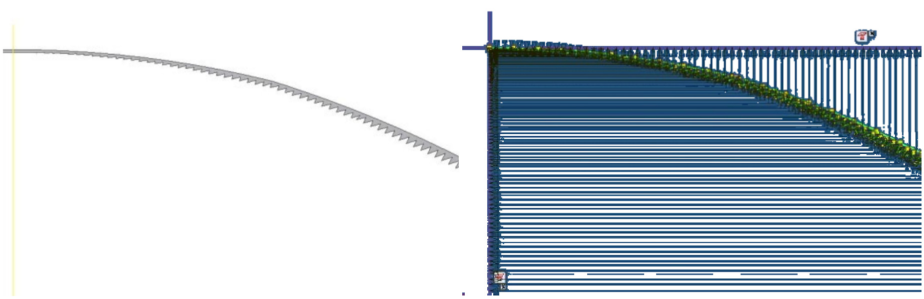

Fig. 5. FLC profile and its parameterization in respect to *X* and *Y* axis

There are several ways to apply parameters to the FLC CAD part, and numerous ways were analyzed. A better optimization response was found by adding two dimensions to each prism, one respective to the *"X"* (horizontal) axis and the other respective to the *"Y"*(vertical) axis, with a total of 246 variables. The FLC profile was then mirrored in respect to the vertical axis. This dimensioning strategy gives the FLC profile fewer constraints, allowing its exterior curvature and internal prisms to change. Each parameter boundary is set up in Dakota's input file, thus SOGA or MOGA method only creates parameters within those sets of boundaries. When limits are too "loose" zero thickness parts are created, resulting in scrap iterations that do not provide any data to the optimization process. If limits are set too "tight" GA has a smaller universe of possible solutions, therefore the optimization process will not produce a significantly better individual compared with the initial model. A macro script was written in Visual Basic (VB) language to do the following actions:

1. Open Inventor template file with FLC part.
2. Update its parameters´ values to the recently created individual by Dakota's MOGA or SOGA method.
3. Export a solid model of the updated FLC part in a neutral format (.sat).
4. Close Autodesk Inventor.

This macro is executed by a command line in a batch executable file [9].

2.2 FLC Optics Simulation

A template file with a ray-tracing simulation was done using Lambda Research TracePro v6.0 software. TracePro cannot simulate moving rays' sources. To simulate the Sun's apparent trajectory throughout the day, a scenario was build consisting of several rays´ sources with properties of a solar angular profile and wavelength distribution from 0.3 to 0.6 μm (visible light range) [10, 11]. Rays' sources are created in a 15° angle increment starting at 45° with respect to the horizontal plane and ending at135°, where each rays' source created 230 rays. Also, a specific irradiance value is set to each rays' source according to model in Figure 1. Table 1 shows the irradiance values on an average sunny day in Monterrey, Mexico, and these values were used for the intensity of the rays' sources in the TracePro simulation.

The next image shows the location and orientation of rays' sources in TracePro simulation template file:

Table 1. Irradiance values for solar rays sources during summer time in Monterrey, Mexico

Rays´ source	*Hour represented*	*Irradiance value (W/m^2)*
45°	9:00	630
60°	10:00	780
75°	11:00	870
90°	12:00	900
105°	13:00	870
120°	14:00	780
135°	15:00	630

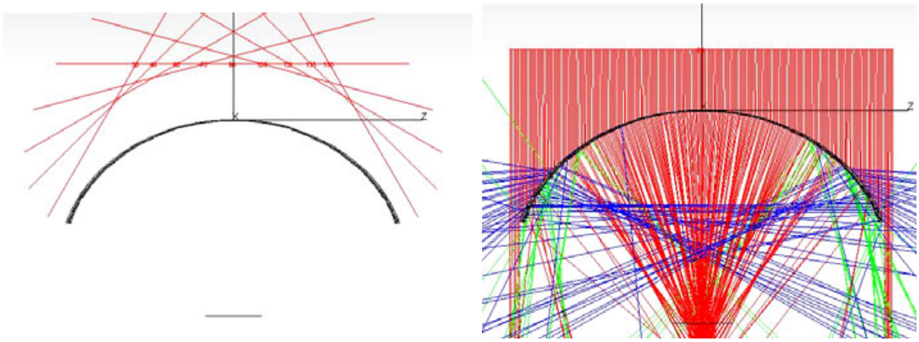

Fig. 6. Front view of rays' sources planes & ray tracing simulation

The FLC solid model is inserted in the template file and moved to a location between the solar rays´ sources and the receptor surface. The rays are generated perpendicular to its source plane towards the FLC model. The rays that fall into the FLC are refracted and concentrated on the receptor plane, which maintains a constant size and location. TracePro analyzes the information about the incident rays flux at the receptor surface. After the simulation is complete, TracePro generates a table with a list of all incident rays at the receptor surface, their original ray source, power fraction and the total power concentrated at the receptor surface.

To complete these actions without any user involvement a macro was programmed (macros in TracePro must be written in LISP programming language).

The macro script actions are listed below:

1. Open simulation template file.
2. Insert FLC solid model.
3. Apply material properties to FLC model.
4. Generate ray sources.
5. Run simulation.
6. Export incident rays data to an ASCCI format file.
7. Close TracePro.

Similar to Autodesk Inventor macro, TracePro macro is executed with a command line in the simulation cycle batch file. An Excel macro is used to extract key information of the total incident rays and the total incident flux from the ASCCI file. For the optimization process using SOGA method, the total incident rays were taken as the result of the objective functions. For MOGA method, the total incident flux was added as a second objective function. These values were assigned to the present individual at the end of each optimization process cycle. Excel macro is executed with a command line from the batch file.

2.3 Batch Script

Dakota input file for this optimization process has an interface section that points to a Windows 7 OS batch script file. This file contains command lines for execution of the simulation cycle used by Dakota to evaluate the present individual. Cycle batch file (*"cycle.bat"*) holds the next lines:

```
//Cycle to evaluate created FLC by GA methods
cd C:\Tesis\BatchScripts\
call ImportParamtoExcel.bat
call OpenInventor.bat
call RunSimTracePro.bat
call Results.bat
call Delete.bat
```

Each line calls for another batch file to run each step of the simulation cycle. *ImportParamtoExcel.bat* executes an Excel macro that changes the format of Dakota's generated ASCCI file to a format that Autodesk Inventor macro understands. *Results.bat* executes an Excel macro to extract the objective functions values and export them to an ASCCI file that Dakota understands. *Delete.bat* is a sub-routine that deletes temporary files created by the optimization process. It is done to avoid same file name issues. Other sub-routines are already detailed above.

3 Results

The FLC model constructed using equations described in section 2.2 was used as a template file and as a base model to be compared with the GA optimized model. Both models were tested using the developed TracePro macro (detailed in section 2.4).

An optimization process was performed using Dakota's SOGA method. The objective function was set to maximize the incident rays at the receptor plane. After more than 1,660 cycles, the FLC with the next fitness values were created:

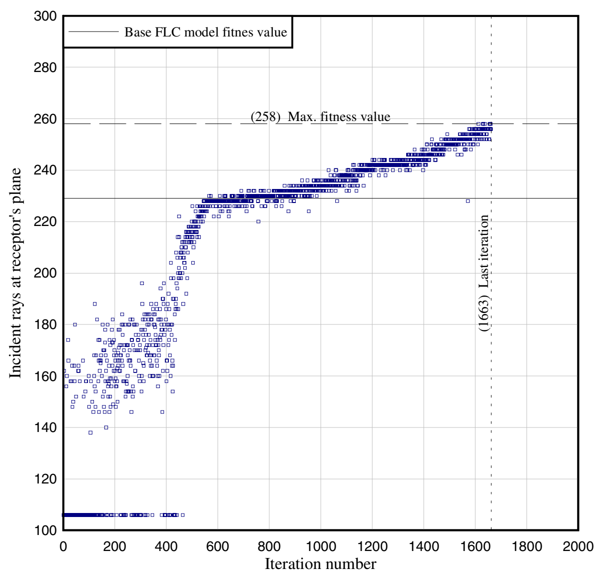

Fig. 7. FLC fitness value progress using SOGA method. Objective function: Maximize incident rays at the receptor's plane

The above chart represents the fitness value of each FLC created by the optimization process. SOGA parameters must be setup in Dakota's input file; a copy of such parameters is presented next:

```
method, soga                          // Method selection
max_function_evaluations = 5000      // First generation is created

initialization_type unique_random   // randomly
crossover_type shuffle_random        // Number of parents for new
num_offspring = 2 num_parents = 2   // individual
crossover_rate = 0.8 //Probability of crossover of a selected
                     // individual
mutation_type replace_uniform
mutation_rate = 0.1  //Probability of mutation of genes of any
                     // individual in the present population
```

An improvement of FLC design can be seen after 500 cycles. After 1663 cycles, SOGA termination parameters concluded that no further significant improvement can be found and optimization process was concluded. The best individual was ranked with a fitness value of 258 incident rays at the receptor's plane. The same simulation macro ranked the base FLC model with a fitness value of 229. Comparing these two values GA FLC is about 12% more efficient that the base FLC model.

Incident rays do not necessary represent the amount of power being concentrated at the receptors plane since all rays, after been refracted by the FLC, loose a different amount of power depending on its incident angle and FLC material properties (refraction index, absorption, etc). To take account for the concentrated power at the receptor's plane, Dakota's MOGA method (Multiple Objective Genetic Algorithm) was used. Maximizing incident flux and rays at the receptor plane were set as the second object function for the next optimization process. Each rays source generated 230 rays with the equivalent of 1 watt of power per ray in order to count the flux concentration. After more than 1200 cycles, the optimization process had the next fitness improvement with respect to the base FLC:

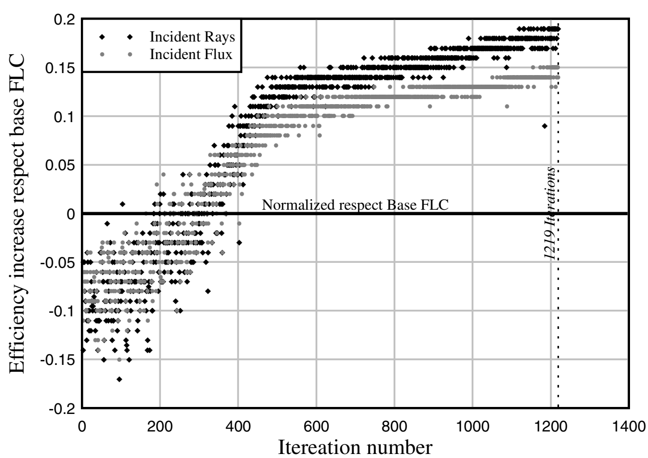

Fig. 8. GA FLC fitness values progress using MOGA method. Each dot represents a FLC model (individual) created by the GA optimization process.

MOGA's method parameters were set up similar to SOGA's. Using two objective functions in the optimization process resulted in a FLC optimized model with an increment of the Incident Rays´ fitness value to 20% and the Incident Flux to 16%, compared to the base FLC model. A series of images of the fittest individual found in the optimization process is shown below.

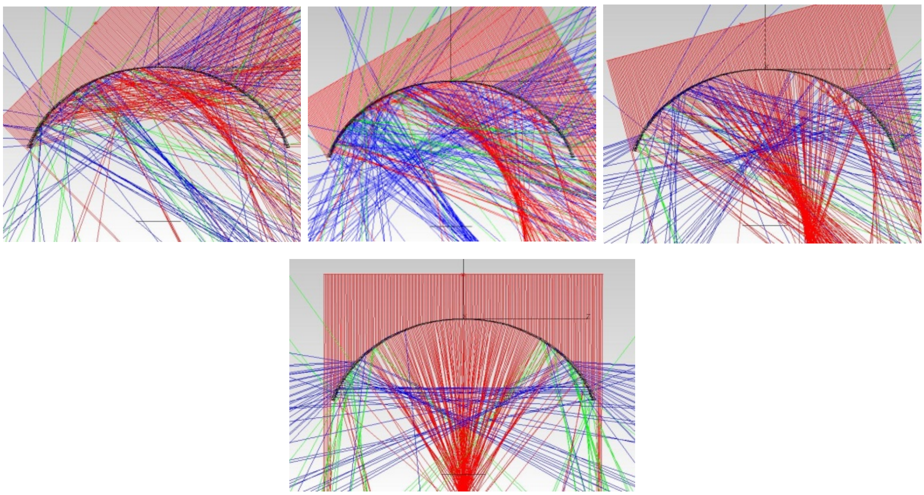

Fig. 9. Ray-tracing simulation with rays sources at 45°, 60°, 75° and 90° respectively. Results for rays' sources at 105°, 120° and 135° can be obtained by mirroring above simulation results by its vertical axis. Red rays have a 66% to 100% of the original ray (prior refraction) flux; blue rays have a 33% to 66% of the original ray flux.

TracePro ray tracing simulation shows the development of a second focus (marked with blue rays) that does not exist in the base FLC model, refracting more rays towards the receptor's plane. The location of the principal focus (marked with red rays) moves due a change of the incident angle at which rays reach the exterior surface of the FLC, reducing significantly its overall efficiency. The following table

Table 2. Ray and flux concentrations overall efficiency in TracePro simulation scenario

Rays Source Inclination Angle	Percentage of incident flux respect refracted flux by the FLC		
	FLC Base Model	GA FLC Model	Without any device
45°	2.33%	5.35%	6%
60°	2.84%	24.29%	7%
75°	3.48%	4.19%	8%
90°	67.36%	62.83%	8%
105°	3.48%	4.19%	8%
120°	2.84%	24.29%	7%
135°	2.33%	5.35%	6%
Average	**12.09%**	**18.64%**	**6.96%**

compares the efficiency of base FLC model, the GA optimized FLC model, and the case of not using any device to concentrate rays into the receptor's plane.

The difference between GA FLC and conventional FLC may seem insignificant due the movement of focus and the fixed receptor's plane. However, the receptor plane only took an average of 12.1% of the total refracted power using the calculated base FLC and 18.6% with GA FLC, which is about 2.6 times more than not using any device. Another approach is to add more receptor planes at key locations, increasing the overall efficiency by reflecting concentrated rays toward a new receptor without shadowing each other. The next image shows the location of multiple receptors:

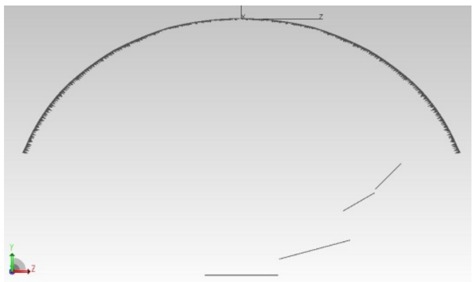

Fig. 10. Multiple receptors positioned to reflect concentrated rays toward a single fixed spot. Only half of the receptors are being used for the sake of the simulation; the other half can be mirrored by the FLC vertical axis (*y axis*).

Using the above configuration, most of the rays and flux refracted by the FLC are being concentrated into the receptors. The overall efficiency is shown in Table 3. Receptors can be Fresnel mirrors, which are capable of reflecting incident rays and flux into a fixed receptor.

Table 3. Overall efficiency using multiple receptors for GA optimized FLC

Source Inclination (Degrees)	*Time (Hours)*	*Incident Flux percentage relative to GA FLC refracted flux*				
		Receptor 1	Receptor 2	Receptor 3	Receptor 4	Total Efficiency
45	9:00	5.35%	3.15%	0.99%	**15.06%**	24.55%
60	10:00	4.29%	3.69%	**26.46%**	9.60%	44.04%
75	11:00	5.62%	**62.14%**	3.49%	3.21%	74.46%
90	12:00	**62.83%**	7.09%	2.17%	1.75%	73.84%
105	13:00	5.62%	**62.14%**	3.49%	3.21%	74.46%
120	14:00	4.29%	3.69%	**26.46%**	9.60%	44.04%
135	15:00	5.35%	3.15%	0.99%	**15.06%**	24.55%
					Average:	**51.5%**

4 Conclusions and Future Work

A final ideal result of a passive tracking device has not yet been reached. As can be seen in the results section, concentrated rays spot focus moves in a three dimensional trajectory depending on the hour of the day (due to Earth's principal rotational movement) and season of the year (due the tilt of the Earth's axis). Nevertheless, applying GA to a shaped Fresnel lens created a more efficient device to concentrate and track solar energy. The strategy used of dimensioning and constraining the FLC profile gave enough freedom to the profile that it allowed the GA methods to create better fitted individuals (FLCs).

A double layer FLC was developed to accomplish spot concentration with a single curvature device. For future work, additional stages of concentration, either a third layer of Fresnel lens or a mirror to the system, can be applied. Using a first concentration stage of 40 suns and a second of 2.5 suns will give a total of 100 suns, enough to achieve 1000ºC on the final receptor with a minimal 4 to 8 percent of extra energy loss due the use of a second reflection or refraction respectively (estimated by PMMA refraction index and a typical mirror film reflection index) [14].

The FLC´s main objective is to concentrate solar rays into a fixed thermal tank for thermodynamic purposes. Concentrated rays must enter the tank from below; therefore, an upwards reflection of concentrated rays must be done after the refraction of solar rays by the FLC. Independent Fresnel mirrors can be set on the focus trajectory with specific orientation to reflect FLC concentrated rays toward the fixed tank. Such mirrors´ design and position must be calculated and optimized to minimize energy losses. A more elaborated ray tracing simulation must be accomplished to help the GA to generate FLC models that refract rays closer to the receptors.

Acknowledgments

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Automatic Extraction of a Contradiction Genealogic Tree from Optimization with an Object-Oriented Simulator

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Abstract. In order to go beyond optimization strategies in Computer Aided Innovation, it has been demonstrated that model changes are required [1,2] during Inventive Problem Solving Process (IPSP). TRIZ proposes a universal way of generating model changes thanks to contradiction statement and contradiction solving but it does not provide methods or tools for obtainting them from typical CAD or other kind of standard data. The aim of the following paper is to propose an algorithm which extracts from an object-oriented simulator a "genealogy" of contradictions systems (both physical and technical contradictions) and formulates corresponding Substance-Field models at the basis of TRIZ Inventive Standard application. This algorithm is fed by optimizations performed on various assemblages of objects constituting the simulator program. It helps disclosing contradictions that cannot be seen by domain experts due to high complexity of problem and is an additional step towards formalization and integration of TRIZ models.

Keywords: Optimization, Inventive design, Hilbert space, TRIZ, ARIZ, Contradiction system, Problem formulation.

1 Introduction

Various authors have proposed enhancements of problem formulation in border of TRIZ. These methods are dedicated to improve effectiveness and efficiency of Inventive Problem Solving Process (IPSP). For concision purpose, it is not discussed in detail how those approaches contribute to that goal and what elements of the puzzle are still missing. It is at least useful to mention that

- some authors explore problem formulation and contradiction statement based on networks of non formalized data [3,4,5,6,7,8,9 and 10], whereas others have proposed to use mathematically formalized knowledge in order to disclose geometrical contradictions (a specific kind of physical contradictions) by using topological optimization algorithm[11] or disclose generalized contradictions by using CSP or design of experiments [12,13];
- a theoretical framework that enables comparison of such approaches still requires to be built (this article is a step towards building this framework).

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1.1 Optimization in an Infinite Dimensional Design Space

Several facets of modeling activities and search strategies when using ARIZ 85-C [14] (hereafter named ARIZ), a supposed convergent IPSP developed in border of TRIZ have been studied in [15]. "Convergent" should be understood as the property of the algorithm to provide a set of successive partial solutions that satisfy step by step more and more requirements of the design problem, until all requirements are satisfied. Since the objects (i.e elements, properties, physical relations) that constitute the various partial solutions and the requirements are not entirely known at the beginning and are disclosed on the way, this study has been performed in an infinite dimensional space. It has been proposed that parameters disclosed to describe objects handled during ARIZ are preexisting dimensions of the infinite dimension space. Define and reformulate contradictions at several system levels is a cognitive pattern in that space. This article goes a step further in direction of a mathematical formalization of search strategies in such a space.

1.2 Motivations

The algorithm of contradiction genealogic tree extraction is proposed hereafter in order to:

- Provide means of complex problems analysis by studying interaction between unusual elements, when expert's knowledge is lacking;
- Disclose rapidly multi system-level problem statement;
- Provide quantitative means of choosing which contradiction of a contradiction system has to be solved in first part of ARIZ.

The following article is more particularly focussed on formalizing the interaction of three elements of TRIZ (system view, contradiction systems, Su-Field models). The contribution proposed may also help to understand in the future how other elements of TRIZ (not considered in this paper) interact with the three elements selected, when performing ARIZ.

With a more general perspective, mathematical formalization of ARIZ search strategy in an infinite dimension space may enable a combination with evolutionary computation [16,17 and 18] strategies for improving IPSP efficiency and effectiveness. To the knowledge of authors, no model, enabling to understand the convergence of ARIZ, have been proposed, although empirical results have shown ARIZ is an algorithm that converges towards solutions for a vast range of complex design problems. It is expected that elements of models developed for ARIZ study may be easily extended in order to depict other IPSP. It will so contribute to form a relevant meta-model of all IPSP.

1.3 Paper Organization

The paper begins with some reminders about invention and optimization problems.

The second part of the paper describes the generic algorithm for extracting the contradiction genealogic tree with their associated Su-Field models.

The third part is devoted to application of this algorithm on a T shaped concrete beam example.

Last part is a discussion about the limitations of the approach, the contributions brought by the genealogic tree and the expected results that may be derived from it.

2 Optimization and Invention Problem Models

2.1 From Optimization Problem

Let us consider a computer simulator X. {P}={P[1], P[2], P[3],…} are input parameters of the simulator X. The simulator may enable these parameters to vary in a predefined range. When a value is given to each input parameter, we name this set of values a configuration of X. The simulator is constituted of objective and constraint functions. We have named objective function Evaluation Parameter and noted {EP} = {EP[0]}. Constraint functions are named Constraint Requirements and noted {CR}={CR[1], CR[2], CR[3], …}.

An optimization problem consists in finding the set of input parameter values that lead to the best value of objective functions while satisfying constraint functions. In the article, we restrain ourselves to mono-objective optimizations. During optimization, we are interested in the various quantitative values taken by evaluation parameter for different configurations in order to compare these configurations and in knowing about the satisfaction of constraint requirements. This is given hereafter by Boolean values, either satisfied (true) or not satisfied (false). However, for computation purpose hereafter, we may also refer to a numerical value to measure variations of the distance to the threshold delimiting satisfied or not satisfied constraints.

An optimization result will be described with the following notations:

- P_0 are the values of {P} that optimize EP[1] while keeping all constraints {CR} satisfied. P_0 is the result of this optimization problem and is a particular configuration of X;
- $P_1, P_2, ..., P_i, ...$ are configurations obtained by optimizing parameters {P} to improve EP[1] when the ith constraint CR[i] is relaxed. The result of such an optimization problem will either lead to break the constraint, i.e. $CR[i](P_i) = false$ or to satisfy the constraint, i.e. $CR[i](P_i) = true$ if the constraint had no influence on P_0. In the article, we restrain ourselves to mono-constraint relaxation.

2.2 To Invention Problem

We may then consider:

- (P_0, P_i) is the couple formed by the two configurations P_0 and P_i;
- if $P_0 \neq P_i$, {P} is known as the action parameter, P_0 and P_i as the couple of opposite values of this action parameter, EP[0] and CR[i] as respectively the evaluation parameters and constraint requirement of a contradiction system noted $CS\ [0; i]$. Those elements are depicted on Fig.1. NB: In the article, we distinguish between evaluation parameters and constraint requirements. The two of them may be known indifferently as evaluation parameters in TRIZ literature [2] and this distinction is introduced here for convenience purpose. The contradictions systems considered hereafter will always involve an evaluation parameter and a constraint requirement. The restriction to this particular type of contradiction systems will be discussed in section 4.

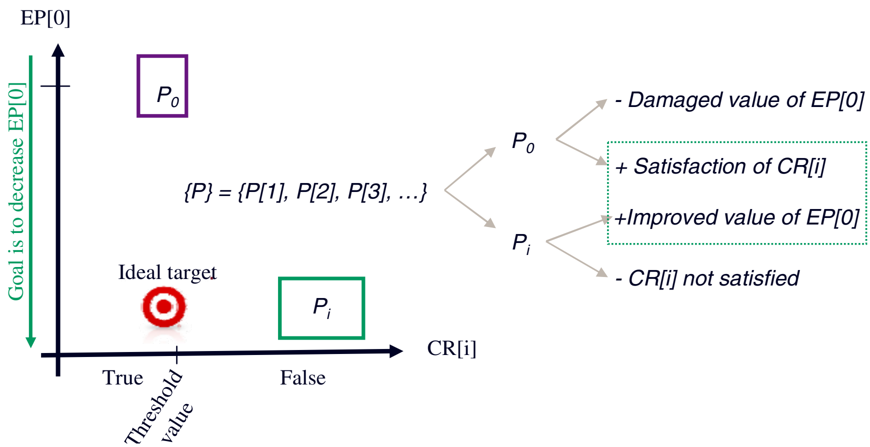


Fig. 1. Contradiction System CS[0;i]

In border of TRIZ, inventive problem solving consists in finding means of obtaining satisfaction of constraint and improved value of EP[0], without generating new problems in the system. ARIZ, for instance, is a cognitive algorithm to perform such a task in a more or less controlled manner. For our concern, the important thing is that this algorithm uses three TRIZ models in particular:

- contradiction system, which link technical to physical contradiction
- system view
- Su-Field models which depict the nature of interaction between elements involved in a contradiction system.

For details about these models, insight about convergence control during ARIZ IPSP, please refer to [19].

2.3 Reformulate Various Invention Problems Linked with the Former One

We may view any configuration P as an assemblage of components (known as sub-systems in border of TRIZ). For the simulator X, which computes the behaviour of any configuration, this decomposition of each configuration may be linked to an object-oriented way of programming the functions of X. Details concerning common points and differences between those concepts coming from optimization, software science and TRIZ background are not discussed in this article but are to be found in an upcoming paper. For clarity purpose, we remind hereafter few basic and simplified elements concerning the structure of an object oriented program that will be a key resource in the proposed contradiction tree extraction algorithm.

In such software architecture, the simulator is decomposed into various components known as class of objects. An object is built by providing particular values to the arguments of a class. On Fig.2, the simulator X is depicted as a graph of classes O[m] (with boxes around). Each class defines the characteristics of all the objects (noted hereafter O_m) it enables to build. Construction of objects of each class requires providing as argument:

- Objects of the classes depicted at next level and connected with arrow (in boxes)

– Input parameters depicted at next level and connected with a line (circled parameter).

The class also provides to any of its object additional functions that depict things the object can do. These functions are noted O[m].F[k] and depicted on Fig.2 with a triangle around. They will be used hereafter as partial evaluation parameters and constraint requirements in the decomposition of invention problem. The function O[m].F[k] of the class O[m] takes as argument either input parameters of O[m] (like P[i] on Fig.2 for instance), or results returned by functions of objects passed as arguments of O[m] (result returned by O[f].F[l] on Fig.2 for instance). We will note $O_m.F_k$ the result returned by O[m].F[k].

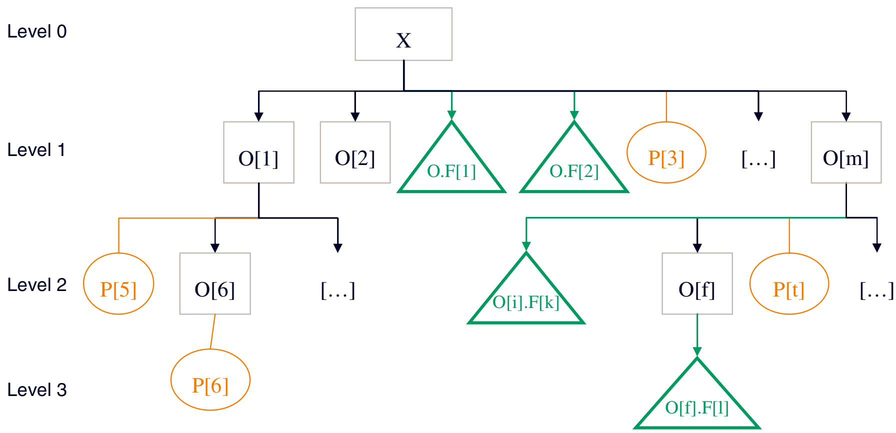


Fig. 2. Structure of an object-oriented simulation program. Boxes are class of objects; circles are parameters; triangles are functions linking parameters and functions of other classes of the considered level.

The object-oriented program on Fig.2 will then take the following generic form:

```
# Definition of classes and their instances
[…]
        Class Object_i

        # constructor
                Def_init_(Of, … other objects,  Pt,… other parameters)
                [...]  # provide the values of the arguments to parameters of object

        # definition of the characteristics of the class (properties and methods)
                Fk = a formula that may involve Of, Pt, etc…
                […]   # define of other functions


# Main part of the program
        Of = Object_f()
```

Oi = Object_i(Of, value of Pt, …)
O6 = Object_6(value of P7)
O3 = Object_3()
O2 = Object_2(value of P5, O6, …)
O0 = Object_0(O2, O3, P4, …, Oi)

This decomposition of a system into components is useful to reformulate the invention problem at those levels. At each level of the decomposition, there may be (or not) inventive problems that have impact on the inventive problem at previous level of decomposition. A way to reformulate contradictions at next or previous level has been proposed in [15]. Such a reformulation is useful when one tries to control which part of the system will change and which part will remain as it is during ARIZ IPSP. This mini-algorithm of contradiction statement formulation and reformulation will be described in a more formalized manner in the next section. The algorithm proposed also goes a step further since it enables the automation of Su-Field models construction for each contradiction system disclosed.

3 The Contradiction Genealogic Tree Extraction Algorithm

3.1 Definitions and Notations

The contradiction genealogic tree is obtained thanks to a sequence of objects generated by solving various optimization problems.
$P_{0.m}$ is the configuration obtained by solving the following optimization problem:

- try to improve input parameters leading to O[m] variation (i.e arguments of O[m], for instance P[t] or parameters of objects built by classes at higher level of decomposition, arguments of O[f] for instance) to improve EP[0]. We will shortly say that component O_m of $P_{0.m}$ was mobile during optimization;
- while keeping values of other input parameters of X constant during the computation, we will then say that other components of $P_{0.m}$ were fixed during optimization;
- relax CR[i].

By symmetry, $P_{i.m}$ is obtained by optimizing parameters of O[m] to improve EP[0], while satisfying CR[i] (and all other constraints) and keeping other components of P_i constant. $(P_0 , P_{0.m})$ and $(P_{i.m}, P_i)$ form then respectively the two contradiction systems CS[0;0.m] and CS[i.m;i];

- EP[0;i]=EP[0] and CR[0;i]=CR[i] are the evaluation parameter and the constraint requirement of CS[0;0.m] and CS[i.m;i]
- CS[0;i] is then the parent of CS[0;0.m], which is the child of CS[0;i] in the contradiction tree (Fig.4);
- Su-field models attached to the contradiction system CS[0;0.m] form a list noted SF[0;0.m] and depict the nature of unsatisfying relationships between mobile component O_m and other components of P_0 remained fixed during optimization.

How to built Su-Field models will be detailed in the next section.

− These other components of P_0 are named adjacent components of O_m.

The notations above remain valid when the indexes "0" and "i" are replaced by combination of index obtained when following the algorithm like $0.[...].m \neq 0$ or $i.[...] \neq i$. If CS[i;j] is the parent of CS[i;i.m], CS[i;i.m] takes the generic form depicted on Fig.3. By extension, we will also consider input parameters as components, following the same computation process described above, i.e. O[m] may be substituted by P[4] without any changes in the previously defined notations.

The goal of the algorithm is to extract a contradiction genealogic tree as depicted on Fig.4. Each node of the genealogic tree is a contradiction system to which is bound Su-Field models. The algorithm acting upon the object-oriented simulator consists of

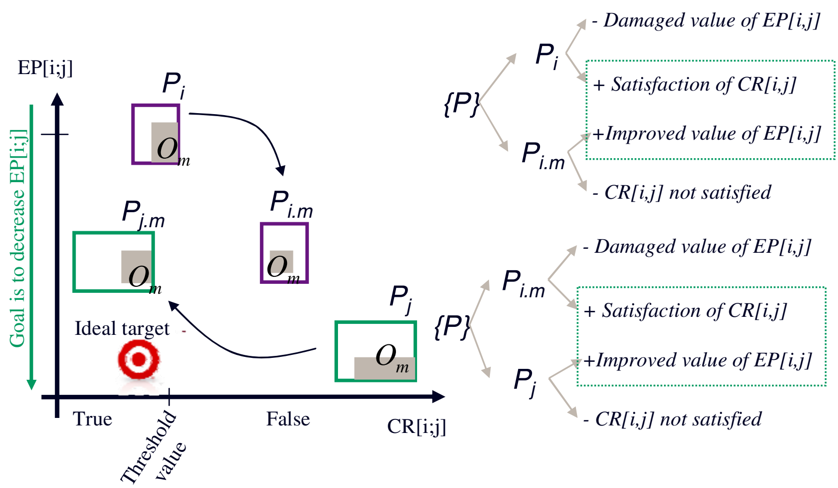


Fig. 3. The two contradiction systems CS[i;j.m] and CS[i.m;j]]

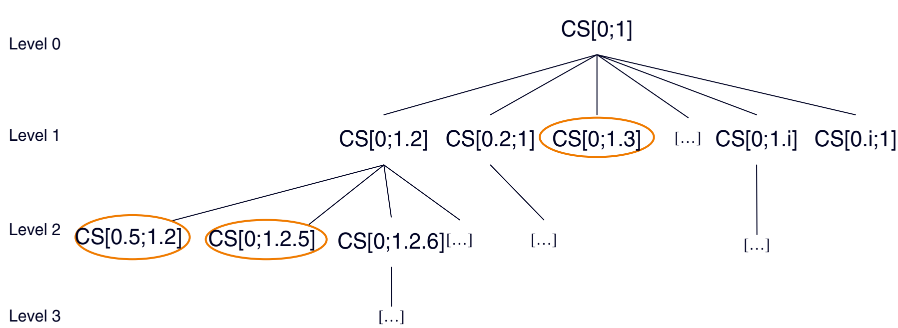


Fig. 4. Partial contradiction genealogic tree related to decomposition depicted on Fig.2. The branch CS[0;1] is partially developed. Circled contradictions systems are leaves of the tree, which means that their physical contradiction involves a single input parameter.

a succession (with loops) of elementary steps detailed in Table 1. An example of application is proposed in part 4.

3.2 Elementary Steps of the Algorithm

The algorithm proposed hereafter is a series of steps described in Table 1 and are repeated until reaching the last level of decomposition.

Table 1. Elementary steps of the algorithm

N°	Function	Details on how to perform the step
1	Obtain a first set of technical contradictions	Optimize {P} in order to improve EP[0] while relaxing the constraint CR[i]. Constraints are to be relaxed one by one.
2	Identify contradiction system CS[i;j.m] that is a child of CS[i;j], $\forall O_m$ a component of Pi.	Optimize parameters of O[m] to improve EP[i;j], while keeping adjacent components to the values they have in Pi and relaxing CR[i;j]. O_m is the sole varying component of Pi during optimization. If a component is shared between varying and non varying components, it should not vary during the optimization. If $P_{i.m} = P_i$, there is no contradiction.
3	Identify the contradiction system CS[i.m;j] that is a child of CS[i;j], $\forall O_m$ a component of Pj.	Optimize parameters of O[m] to satisfy CR[i;j], while keeping other component fixed and improving EP[i;j]. If a component is shared among varying and non varying components, it should not vary during the optimization. If $X_{i.m} = X_i$ there is no contradiction.
4	State Su-Field models of CS[i;j.m].	The nature of relationships between O_m and its various adjacent components O_u in the configuration P_i (resp. $P_{j.m}$) is disclosed by examination of EP[i;j.m] (resp. CR[i;j.m]) variations. Variations in EP[i;j.m] (resp. CR[i;j.m]) = f(O[m].F[1],O[m].F[k],O[m].F[l], …) take the following generic form: $$\begin{matrix}\Delta EP[i;j.m] \\ (resp.\Delta CR[i;j.m])\end{matrix} = \left\vert \begin{matrix} \frac{\partial f}{\partial O[m].F[1]}\Delta O[m].F[1] \\ \ldots \\ \frac{\partial f}{\partial O[m].F[k]}\Delta O[m].F[k] \\ \ldots \\ \frac{\partial f}{\partial O[m].F[l]}\Delta O[m].F[l] \end{matrix} \right.$$ For each variation function, the analysis proposed in table2 has to be performed.
5	State Su-Field models of CS[i.m;j]	The nature of relationships between O_m and its various adjacent

Table 1.(*Continued*)

		components O_u is disclosed by examination of EP[i.m;j] (resp. CR[i.m;j]) variations, following the same method than step 4 above.
6	Create new nodes in contradiction genealogic tree	Insert CS[i.m;j], CS[i;j.m] and their associated Su-Field models as child of CS[i;j] in contradiction genealogic tree.
7	Disclose EP[i.m;j] (resp. EP[i;j.m]) and CR[i.m;j] (resp.CR[i:j.m]) of CS[i.m;j]	These functions are obtained by replacing parameters of P_i (resp. P_j) that remained constant during optimization (i.e. input parameters involving adjacent components of O_m) by their numerical values in EP[i;j] and CR[i;j]. This operation provides new functions (EP[i.m;j] and CS[i;j.m]) that are themselves two functions of the functions O[m].F[k], $(\forall k)$ that belong to O[m].

Table 2. Interpretation of mathematical relations leading to SF[i;j.m]

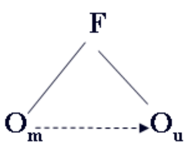
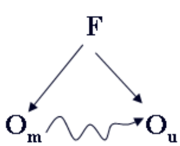
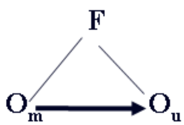
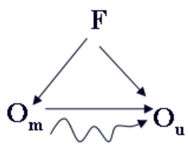
Su-Field Model	Variations to be examined in Evaluation Parameter and Constraint Requirement. EP and CR may be handled in the same way. For concision purpose, only EP analysis has been developed.
	If $\Delta EP[i;j.m]\big|_{P_i \to P_{j.m}} \times \frac{\partial f}{\partial O[m].F[k]}(P_i) > 0$, then $O_m.F_k$ and so O_m has an insufficient action on all the adjacent components O_u involved in the expression of $\frac{\partial f}{\partial O[m].F[k]}$. A Su-Field is drawn for each O_u. NB: if several components are involved, it may be considered in a first approach that O_m has an action on the relationship between these objects. This point still requires to be clarified.
	If $\Delta EP[i;j.m]\big|_{P_i \to P_{j.m}} \times \frac{\partial f}{\partial O[m].F[k]}(P_i) < 0$ and $\frac{\partial f}{\partial O[m].F[k]}$ is a constant function, O_m has a negative effect on itself.
	If $\Delta EP[i;j.m]\big|_{P_i \to P_{j.m}} \times \frac{\partial f}{\partial O[m].F[k]}(P_i) < 0$, and O[m].F[k] can be null in EP[i;j.m], then O_m has an harmful

Table 2.(*Continued*)

	action on all the adjacent components involved in the expression of $\frac{\partial f}{\partial O[m].F[k]}$. A Su-Field is drawn for each O_u. NB: if several components are involved, it may be considered that O_m has an action on the relationship between these components. This point still requires to be clarified.
	If $\Delta EP[i; j.m]\Big\vert_{P_i \to P_{j.m}} \times \frac{\partial f}{\partial O[m].F[k]}(P_i) < 0$, and $O_m.F_k$ cannot be null in EP[i;j.m] (division for instance), then O_m has an excessive action on all the adjacent components involved in expression of $\frac{\partial f}{\partial O[m].F[k]}$. A Su-Field is drawn for each O_u.
	If the analysis of EP[i;j.m] (resp. CR[i;j.m]) leads to extraction of an harmful and an insufficient action between O_m and the same other components, it means there is both useful and harmful relationships between them and the standards are transformed into this last category of standard.

3.3 The Loops to be Performed

The steps of algorithm have to be performed in the following order:

```
For each constraint requirements i
    Perform step 1
    Level = top-level
    node=O0
      For each level
        For each node of the level
          For each component of the node
            Perform steps 2,3,4,5,6,7
            node=next node at same level
        level=next level
        node=first node of the level
```

Last nodes of the genealogic tree are leaves, the physical contradictions of which involve a single input parameter.

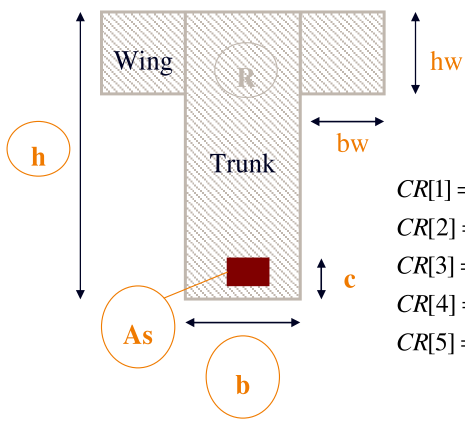
4 Application of the Algorithm on an Example

4.1 Optimization Problem on T Shaped Beam Example

The starting beam from which will be extracted the contradiction tree is the result of the following optimization problem (see Fig.5):

- {P}=(b,h,As,R) are the input parameters of the simulator;
- 5 constraints on geometry of the beam and mechanical resistance should be satisfied in order to obtain feasible solutions. Those constraints are either satisfied (true) or not satisfied (false);
- the cost of the beam is the evaluation parameter to be optimized;
- due to constraints of the environment (insertion of the wings in adjacent concrete slabs for example), c, hw and bw are fixed properties and will not appear hereafter.

The optimized beam is found for a particular set of b, h, As, R values, so that all constraints are satisfied while the cost is minimal. Decrease the cost even more constitutes the starting administrative contradiction of the problem.



$$EP[0] = beam.\mathrm{cost}()$$
$$c = 0.09m$$
$$hw = 0.2m$$
$$bw = 0.4m$$
$$CR[1] = (\sigma < \sigma \max)$$
$$CR[2] = (h\min(= 0.2m) < h < h\max(= 1m))$$
$$CR[3] = (b\min(= 0.2m) < b < b\max(= 1m))$$
$$CR[4] = (R\min(= 10MPa) < R < R\max(= 90MPa))$$
$$CR[5] = (2.h.b < As(cm2) < 40.h.b)$$

Fig. 5. Parametrization of T-shaped beam, Evaluation Parameters, Constraint Requirements and values of parameters that will remain fixed during the whole process

The various optimizations are performed thanks to a free library EASEA [20] and a proprietary interface library. This library has been developed for linking automatically any kind of simulators and building any kind of optimization problem on EASEA standard interface, which enables to construct and solve automatically the various optimization problems handled through the presented generic algorithm.

4.2 Description of the Simulator of T Shaped Beams Used as Example

Warning. Some details concerning the real mathematical equations and computation results are omitted or simplified for concision purpose. Rough numerical values are given in order to clarify examples.

The simulator, provided by courtesy of Lafarge, computes the behaviour of the beam depicted on Fig.5. \

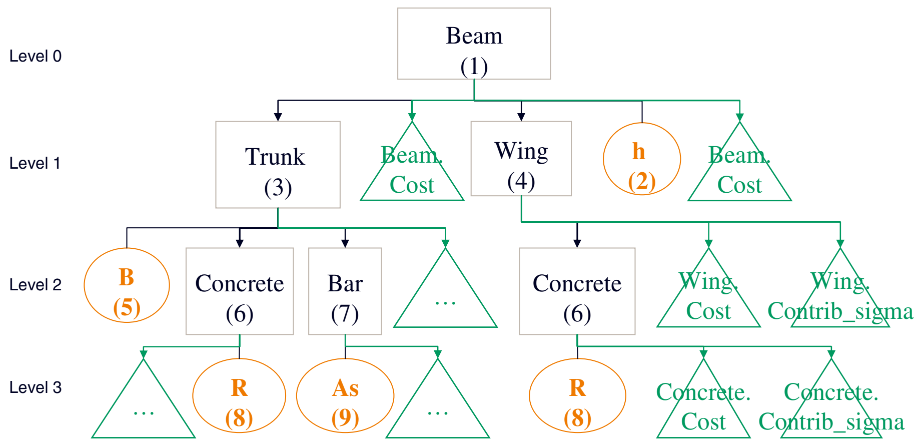


Fig. 6. Structure of the object oriented simulator of T-shaped beam, with functions (triangle), components (box) and input parameters (circle). Numbers provided below each object name are used for easy reference purpose. . Trunk and Wing share the same component Concrete.

The structure of the simulator is an object oriented program (see Fig.6). The simplified code is reproduced below.

```
    # Definition of classes and their instances
            Class Concrete
                        Def_init_(R)
                                    cost = R*100.
                                    contrib_sigma = 1/R
            Class Bar
                        Def_init_(As)
                                    cost = As*900.
                                    contrib_sigma = 1/ (As * 600)
            Class Trunk
                        Def_init_(b, Concrete, Bar)
                                    cost_concrete = 20*b*Concrete.cost
                                    cost_steel = Bar.cost
                                    contrib_sigma = Bar.contrib_sigma – Bar.contrib_sigma^2
                                    …/ (b*Concrete.contrib _sigma)
```

```
Class Wing
        Def_init_(Concrete)
                bw = 0.3
                hw = 0.2
                contrib _sigma = Concrete.contrib _sigma *…
                        hw * sqrt(bw)
                cost = bw*hw*Concrete.cost
Class Beam
        Def_init_(h, Trunk, Wing)
                bt = 0.7
                c = 0.9
                l = 8.1
                cost = h*Trunk.cost_concrete + Trunk.cost_steel +…
                        2*Wing.cost
                sigma = (1/h^2) * Trunk.contrib _sigma +…
                        2* Wing.contrib _sigma

# Main part of the program
    R=10
    As=2.1
    b=1
    h=1
    Concrete = Concrete(R)
    Bar = Bar (As)
    Trunk = Trunk (b, Concrete, Bar)
    Wing = Wing (Concrete)
    Beam = (h, Trunk, Wing)
```

4.3 The Algorithm for Contradiction Genealogic Tree Extraction

Warning. Drawings of optimization results are given with an explanatory purpose only and not as outcome of a real computation.

Let us relax one by one each constraint. Single constraint relaxation may lead (or not) to technical contradiction. In the example, relaxing constraint on hmin for instance has no impact on optimization and so does not lead to a contradiction. However, Fig.7 shows some optimization results P1 and P2 when relaxing constraints $\sigma\max$ and $h\max$ respectively. (P0, P1) and (P0, P2) form respectively the contradiction systems CS[0;1] and CS[0;2] at the level 0 of the genealogic tree (see Fig.16).

Let us focus on CS[0;1] in order to identify physical contradictions at level n°1 of the tree. We may first vary parameter h which is the component n°2 in the object-oriented decomposition (Fig.6). Fig.8 shows contradiction system CS[0;0.2] obtained by using h as a varying component. CS[1.2;1] does not exist since the best value of h does not enable P1.2 to satisfy constraint requirement n°1 on $\sigma\max$.

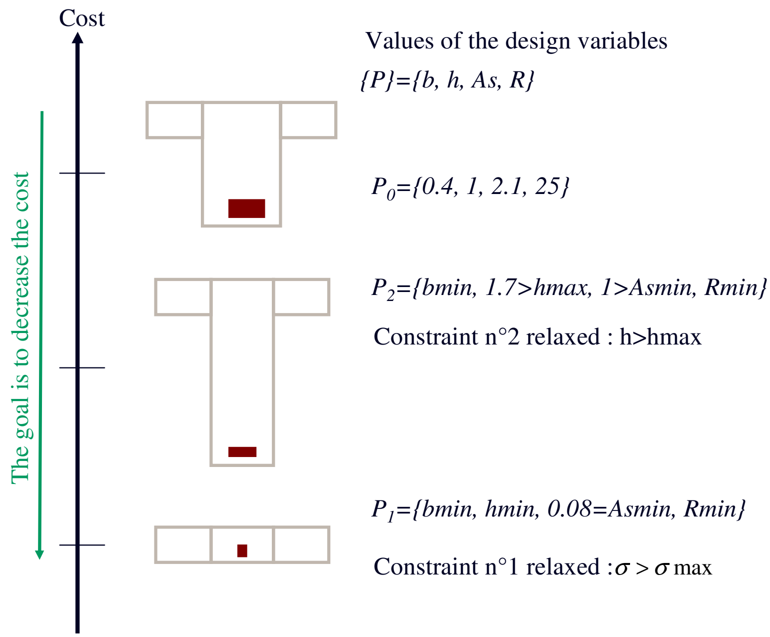


Fig. 7. Results of optimization obtained when relaxing constraints one constraint. P1 is obtained by relaxing $\sigma\max$ and P2 is obtained by $h\max$ relaxation.

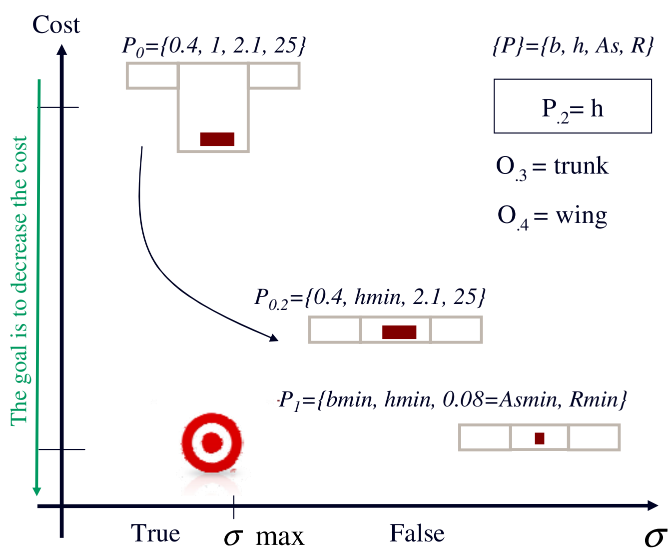


Fig. 8. Configurations P0 and P0.2 involved in CS[0;0.2]. Configuration P0.2 is obtained by optimizing h in order to improve P0 on EP[0;1] while keeping other components of P0 fixed.

Since EP[0]=Beam.cost = h*Trunk.cost_concrete + Trunk.cost_steel + 2*Wing.cost, Δcost = Trunk.cost_concrete* Δh and Δcost(P0->P0.2) * Trunk.cost_concrete(P0) <0, h has an harmful impact on the trunk. The height increases indeed the cost of concrete in trunk, hence the harmful impact on the trunk in Fig.15. Moreover, CR[1]=sigma = (1/h^2)* Trunk.contrib_sigma + 2 * Wing.contrib_sigma, Δsigma = - (1/h^3) * Trunk.contrib_sigma * Δh and Δ sigma(P0.2->P0) * (- 1/h^3) * Trunk.contrib_sigma >0. The lever length effect on the trunk has indeed a too weak effect on trunk to decrease σ, hence the Su-Field proposed in Fig.9. A new contradiction node can be added in the contradiction genealogic tree (Fig.10). Since CS[0;0.2] is a leave of the tree, the evaluation parameters and constraint requirements functions at sub-level are not evaluated.

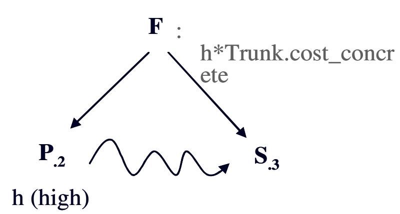
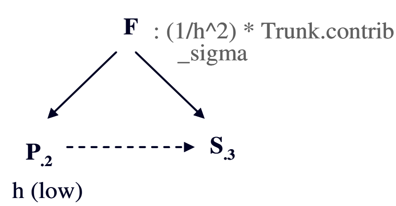
P0={0.4, 1, 2.1, 25}	*P0.2={0.4, hmin, 2.1, 25}*
Sigma : true but Cost : high	Cost : low but Sigma : false
	

Fig. 9. CS[0;0.2] and associated Su-Field models

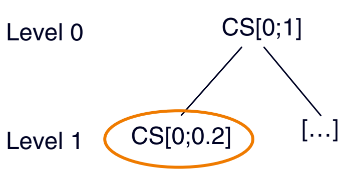


Fig. 10. CS[0;0.2] is a child of CS[0;1] in contradiction genealogic tree

Let us now vary the parameters of the trunk, the component n°3 in the object-oriented decomposition (Fig.8). Fig.11 shows contradiction systems CS[0;0.3] and CS[1.3;1] obtained by using trunk as a varying component.

Since EP[0] = h*Trunk.cost_concrete + Trunk.cost_steel + 2*Wing.cost,

$$\Delta \cos t = \begin{cases} h * \Delta Trunk.\cos t\_concrete \\ \Delta Trunk.\cos t\_steel \end{cases}.$$

Δcost(P0->P0.3)*h(P0)<0, so the trunk has an harmful relationship with h which leads to increase the cost of the beam, hence the harmful impact on height in Fig.12. This relationship is in fact a geometrical relationship. Δcost(P0->P0.3)*1<0, so the trunk has also an harmful impact on itself (Fig.12). It is due to its own cost (due to steel bar inside). Since CR[1]=sigma = (1/h^2) * Trunk.contrib_sigma + 2 * Wing.contrib_sigma, Δ sigma = (1/h^2) * Δ Trunk.contrib_sigma and Δ sigma(P0.3->P0)* (1/h^2) <0. The trunk has a harmful relationship with the height, which leads to increase the stress that the material constituting the beam has to endure, hence the Su-Field proposed in Fig.12. The operations for CS[1.3;1] are the same, only the numerical values change. The two new contradiction nodes can be added in the contradiction genealogic tree.

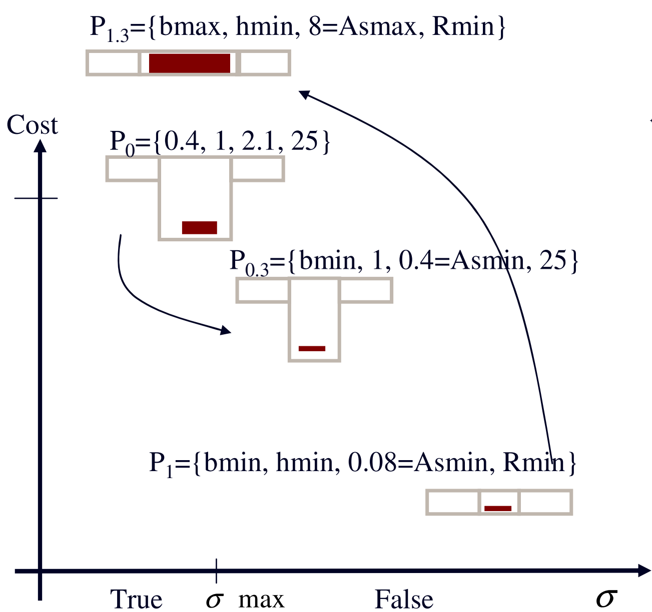


Fig. 11. Configurations P0 and P0.3 involved in CS[0;0.3] and configurations P1.3 and P1 involved in CS[1;3;1]. Configuration P0.3 is obtained by optimizing the trunk while keeping other components of P0 fixed in order to improve P0 on EP[0]. Configuration P1.3 is obtained by optimizing the trunk while keeping other components of P1 fixed in order to satisfy CR[1].

We may now evaluate the evaluation parameter and the constraints requirements of CS[0;0.3] and CS[1.3;1] children. Since EP[0] = Beam.cost= h*Trunk.cost_concrete + Trunk.cost_steel + 2*Wing.cost = h* b * Concrete.cost + Bar.cost + 2* bw* hw* R* 100, EP[0;0.3] = b * Concrete.cost + Bar.cost + 400. and EP[1.3;1] = b * Concrete.cost + Bar.cost + 160.

Symmetrically, CR[1] = (1/h^2)* Trunk.contrib _sigma + 2* Wing.contrib _sigma = (1/h^2)* (Bar.contrib_sigma – Bar.contrib_sigma^2/(b*Concrete.contrib_sigma))+ 2* 1/R * hw * sqrt(bw). So CR[0;0.3]= Bar.contrib_sigma + Bar.contrib_sigma^2/ (b* Concrete.contrib_sigma) + 0.010 and CR[1.3;1]= Bar.contrib_sigma + Bar.contrib_sigma^2/(b*Concrete.contrib_sigma) + 0.025.

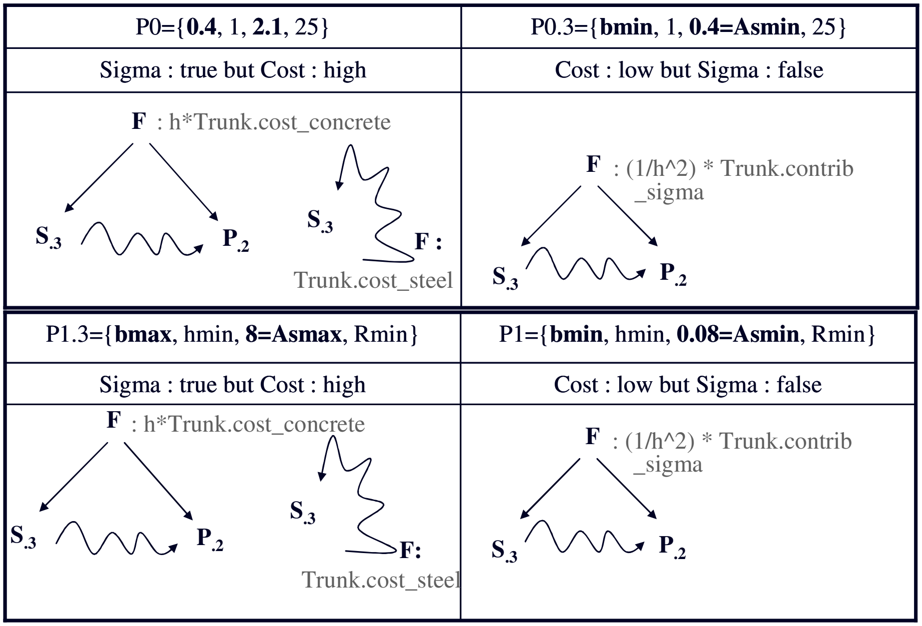


Fig. 12. CS[0;0.3] and CS[1.3;1] and associated Su-Field models. The bold parameters are the parameters varying during optimization. R is assumed to vary but cannot because it is also a parameter of the wing which is fixed.

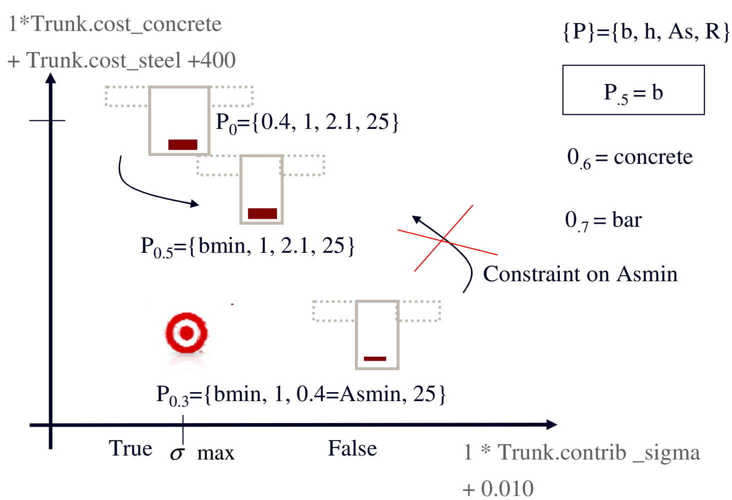
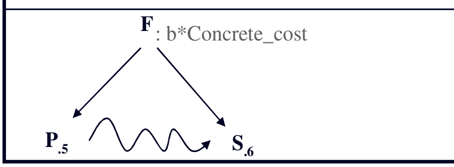


Fig. 13. Configurations P0 and P0.5 involved in CS[0;0.5]. Configuration P0.5 is obtained by optimizing b in order to improve P0 on EP[0;0.3] while keeping other components components of P0 fixed.

Let us now focus on CS[0;0.3] in order to identify physical contradictions at level n°2 of the tree. We may first vary parameter b which is the component n°5 in the object oriented decomposition (Fig.6). Fig.13 shows contradiction system CS[0;0.5] obtained by using b as a varying component. CS[0.3.5;0.3] does not exist since there is no b value that enables P0.3.5 to satisfy constraint requirement n°5 on Asmin.

Since EP[0;0.3] = b * Concrete.cost + Bar.cost + 400. we have Δ EP[0;0.3] = Δ b * Concrete.cost and Δ EP[0;0.3] (P0->P0.5)* Concrete.cost(P0) <0. b has an harmful impact on the concrete due to a geometrical effect that increases the volume of concrete, hence the harmful impact on the concrete modeled in Fig.21. Since CR[0;0.3] = Bar.contrib_sigma + Bar.contrib_sigma^2/ (b*Concrete.contrib_sigma) + 0.010, we have Δ CR[0;0.3](P0.5->P0)* (-Bar.contrib_sigma^2/ (b^2* Concrete.contrib_sigma)>0. b has an insufficient action on the relation between bar and concrete. It is indeed not high enough for elevating the position of neutral axis separating the part of the beam that endures a tensile stress (bottom) and the part that endures a compressive stress (top of the beam), hence the Su-Field proposed in Fig.21. A new contradiction node can be added in the contradiction genealogic tree (Fig.22). Since CS[0;0.5] is a leave of the tree, the evaluation parameters and constraint requirements functions at sub-level are not evaluated.

P0={**0.4**, 1, 2.1, 25}	P0.5={**bmin**, 1, 2.1, 25}
CR[0;0.3](X0) : true but EP[0;0.3](X0) : high	EP[0;0.3](X0.5) : low but CR[0;0.3](X0.5) : false



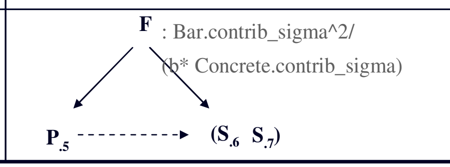


Fig. 14. CS[0;0.5] and associated Su-Field models

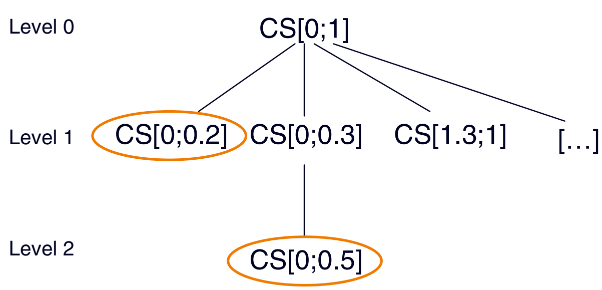


Fig. 15. CS[0;0.5] is a child of CS[0;0.3] in contradiction genealogic tree

Let us focus on CS[1.3;1] in order to identify next physical contradictions at level n°2 of the tree. We may first vary the Bar, which is the component n°7 in the object oriented decomposition (Fig.6). Fig.16 shows contradiction system CS[1.3;1.3.7] obtained by using the bar as a varying component.

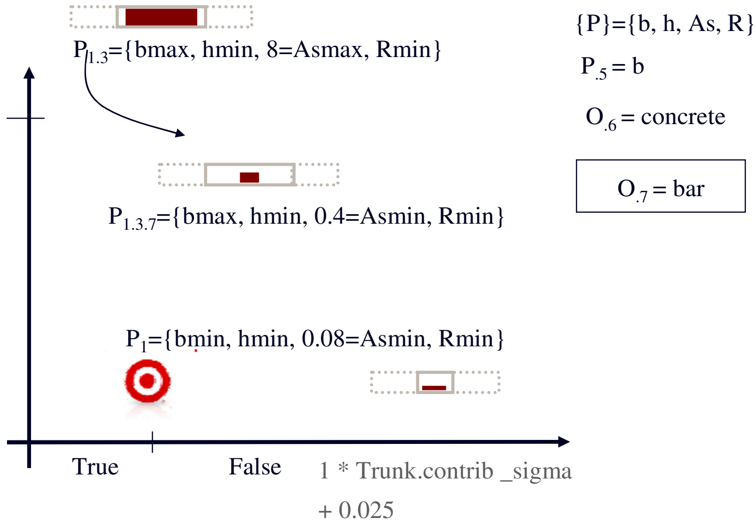


Fig. 16. Configurations P1.3 and P1.3.7 involved in CS[1.3;1.3.7]. Configuration P1.3.7 is obtained by optimizing the bar in order to improve P1.3 on EP[1.3;1] while keeping other components of P1.3 fixed.

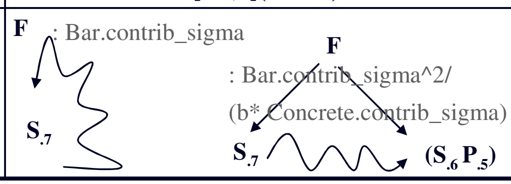
P1.3={bmax, hmin, **8=Asmax**, Rmin}	P1.3.7={bmax, hmin, **0.4=Asmin**, Rmin}
CR[1.3;1](X1.3) : true, but EP[1.3;1](X1.3) : high	EP[1.3;1](X1.3.7) : low but CR[1.3;1](X1.3.7) : false
	

Fig. 17. CS[1.3;1.3.7] and associated Su-Field models

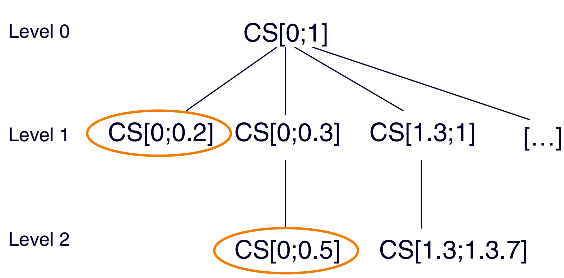


Fig. 18. CS[1.3;1.3.7] is a child of CS[1.3;1] in contradiction genealogic tree

Since EP[1.3;1] = b * Concrete.cost + Bar.cost + 160., we have Δ EP[1;1.3] = Δ b *Concrete.cost and Δ EP[0;0.3] (P1.3->P1.3.7)* 1 < 0. The bar has a harmful impact on itself, hence the Su-Field in Fig.17. The steel that constitutes the bar has indeed a high cost. Since CR[1.3;1] = Bar.contrib_sigma + Bar.contrib_sigma^2 / (b* Concrete.contrib_sigma) + 0.025., we have

$$\Delta CR[1.3;1] = \begin{cases} \Delta Trunk.\cos t\_concrete \\ 2 * Bar.contrib\_sigma / (b * Concrete.contrib\_sigma) \end{cases}.$$

CR[1.3;1](P1.3.7->P1.3)*1 < 0 means that the bar has a harmful action on itself in configuration P1.3.7 since it increases the contribution it has to provide to the beam in order to help resist to the stress. Δ CR[1.3;1](P1.3.7->P1.3)* 2 Bar.contrib_sigma / (b* Concrete.contrib_sigma)< 0. The bar has a harmful action on the relation between concrete and b, hence the Su-Field proposed in Fig.17. It means the configuration of the bar in P1.3.7 tends to oblige b and concrete to increase their contribution to resistance. A new contradiction node can be added in the contradiction genealogic tree (Fig.18).

The algorithm may be continued until all leaves are reached.

5 Discussion and conclusion

The approach of formalization proposed in this article provides insight about the crucial role of components organization when indentifying contradictions consistent with Su-Field modelling and reformulating them. A particular extraction algorithm of those contradictions has been detailed. However, many other TRIZ elements still require to be better formalized in order to obtain a complete framework to define and study convergence of ARIZ and other IPSP.

5.1 What are the Possible Extensions of the Genealogic Contradiction Tree Extraction Algorithm Presented Here-Above?

Table 3. Summary of limitations and opportunities of improvement of the algorithm

Limitations of current algorithm	Work to be performed in the future
Contradiction systems studied are only the ones that involve an evaluation parameter and a constraint requirement of the simulator.	We plan to develop a similar algorithm that starts from technical contradictions generated by decomposing the starting evaluation parameter into two evaluation parameters.
The proposed algorithm is restricted to object-oriented simulator in which the program text of each function of simulator can be formally derived.	The formal derivation has been used for Su-Field analysis. How to extract the Su-Field without formal derivation? The nature of knowledge that is mandatory to extract appropriate information requires to be further studied and we plan to develop alternative solutions for “black-box” simulators.

Table 3.(*Continued*)

The contradiction systems disclosed have all the same structure which enable a straightforward extraction of Su-Field models.	This may be viewed as an additional contribution of the article, since reformulating a contradiction system into Su-Field models has not been yet formalized in part 1 of ARIZ. This lack of consistency in TRIZ models often leads to difficulties of practice for TRIZ beginners. However, it should be studied if the particular structure we propose (in which action parameter concerns a component of the system on which evaluation parameters are defined), enables to disclose all the Su-Field models that may have resulted from a less structured approach. This topic is difficult because such model reformulation may lead to add knowledge previously hidden in mind of ARIZ user.
The algorithm deals and relaxes constraints that were purposely defined as such. It does not enable to define new evaluation parameters.	An extension of this algorithm may also consider the fixed parameters p1…pj as constraints to be relaxed. Other source of embedded information may be also explored. Understanding why a source of information is more relevant than another is also a potential issue?
The algorithm considers only contradiction systems involving two EP (indeed one EP and one CR)	Another extension of the algorithm could consist in relaxing combination of constraints. The management of such "poly-contradictions" cannot be handled with TRIZ-classic tools and may eventually be studied with the purpose of reformulating them into TRIZ-classic contradictions.
In the Su-Field extraction algorithm proposed, it is assumed that, as soon as a mathematical relation exists between evaluation functions of sub-systems, a direct interaction involving a physical field also exists.	The proposed algorithm is based on the paradigm that an object-oriented simulator has been developed in a way that fits to designer representation of a real object (current paradigm in computer science). However, we plan to examine more in detail the similarities and differences in analysis when analyzing systems in TRIZ way and when defining objects to compute quantitative functions in computer science.
If the object-oriented decomposition of the simulator changes, the contradiction systems and Su-Field change.	Are there better system decompositions than others? The proposed algorithm may help us to understand what types of decompositions are leading to the most interesting contradiction systems. It should also be examined in which manner the best decomposition found fits with the 4 elements decomposition model proposed in TRIZ to analyze key elements of any system.
The object-oriented simulator considered from up to now has a simple structure: evaluation parameters and constraint requirements are computed thanks to the same object decomposition, functions involve expression that can be explicitly computed, etc…	NB: the problem generated by complexification of simulators only concerns Su-Fields extraction. Each complexification way could be studied step by step in order to check weather they can be transformed into a canonical way. This problem may also disappear if a Su-Field extraction algorithm is provided, which does not require access to the program text.

Table 3.(*Continued*)

If several components are involved in the Su-Field description, it has been considered that O[m] has an action on the relationship between these objects.	There is no rationale so far for such an interpretation. This point should be examined more in particular in order to understand why this situation occurs (since, based on our knowledge, it seems not to occur when humans perform ARIZ).
The algorithm does not solve the Su-Field model problem!	Merge this contradiction extraction selection approach with an algorithm that automatically provides model change proposals as proposed in [21] may enable to build an algorithm that invents
	A new evolutionary computation paradigm could then consist in starting the design process with very simplistic models and then enhance the modeling approach step by step in a controlled and efficient way. When optimization reaches its limit (either because of the computational complexity of reaching global optimum or because of the unsatisfying value of global optimum), model changes suggested by Inventive Standards may enable to bypass the limits. However, the entire automation of model changes proposed in [21] to support quantitative computation remains an open issue.

5.2 What Does the Proposed Model Contribute To? What Does it Fail to Provide?

Table 4. Summary of contributions and partial results brought in the article

Targets of the research work	Partial answer proposed in the article
Provide means of complex systems analysis, in order to study interaction between elements when expert's knowledge is lacking.	By use of an object oriented simulator, a vast range of contradictions can be stated and organized. Such a systematic extraction may lead to consider configurations not taken into account by experts.
Disclose rapidly multi-system level problem statement	The step by step formalization of contradiction statement process and reformulation at sub-system levels proposed herein may enable a straightforward implementation of the algorithm in computer and so increase the rapidity of problem formulation, providing a simulation program is available. Computer validation will be proposed in a further paper. This result may be improved by developing an algorithm that deals with more complex simulators.
Provide quantitative means of contradiction choice.	Thanks to automation and the capacity to evaluate performances of the sequence of configurations obtained, we expect to build quantitative indicators in order to ease the selection of contradiction. Other criteria of contradiction choice may also be implemented in the algorithm. However, we also expect various aspects linked with the reformulation process in ARIZ to be responsible of difficulty in defining such an impact measure a priori.

Table 4.(*Continued*)

Help formulating Substance-Field models at the basis of TRIZ Inventive Standard application	Su-Field modeling is a direct consequence of mathematical relations at each decomposition level, given an object oriented simulator. Hence Su-Field models of problem are fully determined by the process presented above.
Reduce modelling complexity and modelling work leading to low marginal payoff during inventive problem solving.	Automation enables to obtain problem models in a straightforward manner. However, this relative rapidity has to be put in balance with the invisible work of developing mathematical models and programming the simulator used for extraction.
Control of knowledge handled during IPSP and its source.	Since knowledge is embeded since the beginning in the object oriented code or consists of some elementary mathematical transformations (derivation), no additional knowledge is required for the restricted part or IPSP depicted in this article. This point may be useful for research purpose in inventive problem solving, because it enables to study separately phenomena that are currently always linked (analysis and reformulation process for instance). Moreover, the algorithm may provide unexpected result that will raise questions about "human implicit control" while performing ARIZ. Those control functions may then be eventually implemented in the algorithm, depending on knowledge they are based on.

Acknowledgments

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Technical Facets of a New Methodology to Describe Processes Contemplating Networking of Computer Aided Engineering Methods

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Abstract. Computer Aided Engineering (CAE) methods describe behavior of products and simultaneous validate a product design. From scientific and practical viewpoints, these simulation methods have to be executed and synchronized in a process considering their generic interdependencies. For instance while performing car's door digital validation, various simulations have to be performed e.g. stiffness, crash, forming. According to the dependencies, crash simulation needs results of forming simulation as inputs which authenticate a need of CAE process. So far, the CAE process has been accomplished partially and in a manual way, which make engineers unable to validate a complete product in faster and efficient way. A new methodology to develop a CAE network and deriving an explicit product, phase, and priority oriented CAE process from that is described with concept and implementation in this paper. Major objective of this research work is to improve the quality of simulation by developing computer aided network of CAE methods.

Keywords: CAE Network, CAE Process, Multiphysics Simulation and Simulation Data Management.

1 Introduction

High inspiration to develop the best technical products that satisfy increasing customer requirements on style, quality, comfort, safety, cost and environment protection, is pushing all original equipment manufacturers to work on holistic digital approach from the concept phase to the final phase.

In vehicle development process, the digital validation approach is CAE that enables to simulate almost all the aspects of the product's behaviors in a virtual environment. To validate a product numerous simulations like stiffness analysis, fatigue analysis and fluid analysis are performed. Currently in automotive industries, there is an inefficient interaction among simulations. For holistic design approach a product validation must have to consider dependencies among simulations. For instance, in order to calculate sound pressure level (SPL) around the vehicle occupants' ears, NVH (Noise, Vibration and Harshness) simulation has to be

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performed. In order to calculate the SPL, several inputs are needed, as wind flow evolution, road contact profile, or motor and exhaust behaviors. For a holistic digital approach all these inputs have to be used by NVH in digital form, which is not an optimized process at present. Nowadays, some solutions exist in the area of multidisciplinary simulation; but the factors that define product's holistic behavior and generic dependencies among simulations are not well distinct in digital world [1] [2] [3].

Indeed, the relation between CAD, CAE and CAM in vehicle development process is essential, but this research is concentrated to CAE domain.

2 State of Art

2.1 CAE Process

Vehicle development process made great stride towards the description of workflow and timeline among interdisciplinary domains as shown in Figure1. The generic dependency between CAD and CAE states that CAD department has to finish the responsibilities and handover to CAE department before freezing date. The workflow between these domains and data transferring is a standardized process. Narrowing to CAE domain, it includes various kinds of simulations like stiffness analysis, Crash Analysis, Aero-dynamics; there is a requisite of standardized data work flow among each other. Currently the data flow is executed manually and partially, which results to error prone and time-consuming process.

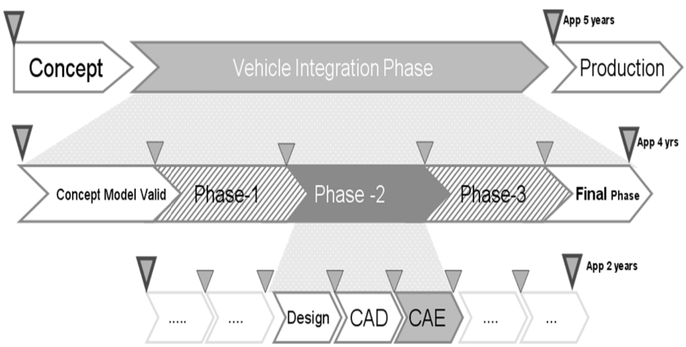

Fig. 1. Vehicle Development Process

Vehicle development process requires a complete integration of CAE process in order to reduce the escalating complexity of simulation data. Presently in most of the industries, CAE process is a parallel process as shown in Figure 2. The simulations are performed independently to each other, even though they are validating a same product. Some processes and solutions help to network simulations but not enough for complete CAE domain.

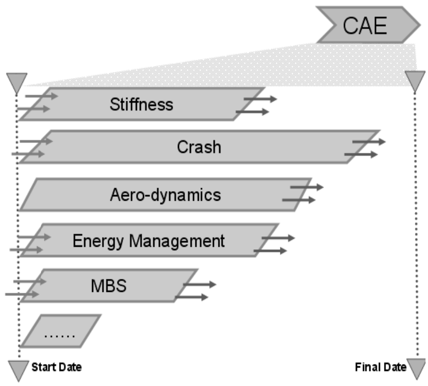

Fig. 2. CAE Phase in Vehicle Development Process

The consequences of deficiency of CAE process are as follows:

- Difficult to co-ordinate the large and versatile CAE structure.
- No controlling on the deadlines.
- No standardized simulation data workflow.
- Manual process results to an error prone and time-Consuming process.
- Unable to validate complete system.
- Dependent on Hardware testing which is a time and money consuming process.

On the contrary, if the workflow among simulations are in the sequential form than it results in extension of development time which is inadequate according to requirements. Time factor plays a major role in describing and optimizing a CAE process. The solutions of these challenges are well described later on. [4][6][15].

2.2 CAE Networking

There are different facets of CAE networking. Simulation data management, Multiphysics simulation and co-simulation platforms are common networking methods.

<u>Simulation Data Management:</u>
Networking of simulation data and results in the data management has not reached the same level of evolution as of product data management systems (PDM systems). Consequently, the results of simulations often fail to fulfill the continuing maturity of product design and development. Feasibility to automate or interpolate various variables is well explained in simulation data management [4] [5] [6] [15].

<u>Multi-physics simulation:</u>
It is a methodology for the design of systems in which strong interactions between disciplines motivates designers to simultaneously manipulate variables in several disciplines. Multidisciplinary tools with numerous interfaces to network FEA, CAD, CFD and control design engineering help to highlight the requirements of digital

holistic approach; though they cannot currently fulfill the needs for complex automobile parts. [7] [8] [9] [10] [15].

Cosimulation platforms:
Modern powerful co-simulation platform like ICOS (Independent Co-Simulation Environment) supports the integration of simulation tools from different domains. Modern coupling algorithms ensure that the – in reality existing – interdependencies between different models are depicted. Parallel to this an ITEA-2 project MODELISAR is ensuring a development of Functional Mock-up which is a next generation of the Digital Mock-up to enable the simulation of the vehicle functional behavior. Nevertheless presently these powerful co-simulation platforms cannot fulfill the needs of a digital holistic approach. [2] [11] [15].

3 A New Methodology

The innovative methodology is integrated to the existing networking methods and fills the gap, which the existing methods are not able to fill. In this section description of the methodology and technical facets are described.

3.1 Description of the methodology

There are two major challenges for building this methodology. First is to create libraries that define the generic dependencies between simulations and between products (in terms of simulation dependencies). These libraries are defines as Generic Relation Matrix (GRM). Second major challenge is to generate automatically a process template according to the generic dependencies.

For a CAE networking, the relation among digital validation methods has to be defined. To characterize the relation following variables has to be defined. The major variables are dependency, mapping, workflow, time as shown in Figure 3.

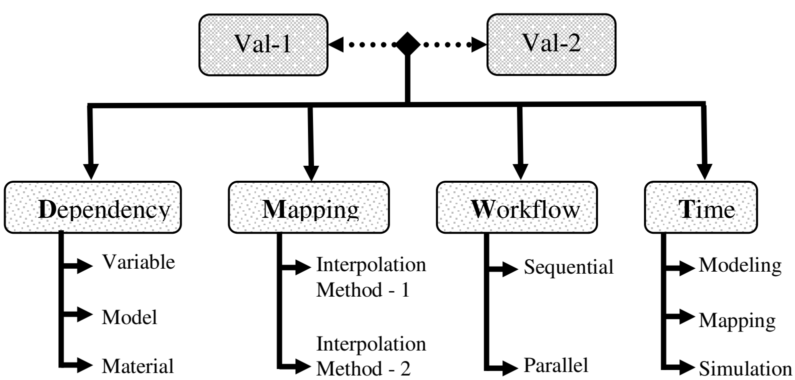

Fig. 3. Generic Validation Relation Factors

Here is an elaborated example to describe the coupling and generic dependencies between NVH simulation and Aeroacustics simulation. Indeed, NVH (Noise, Vibrations and Harshness) can be caused by several sources, from the vehicle itself as well as from the external environment. One of these sources is the wind which acts as distributed forces. Consequently, NVH simulation requires pressure loads distribution *p(t)* in time domain in order to be performed.

At present, in several automotive industries, the transient pressure distribution is imported during prototype phase from wind tunnels tests. In order to optimize and fasten the CAE process, the transient data p(t) can be imported digitally from Aeroacustics simulation (during the CAE phase). This leads to a reduction of dependency on hardware prototypes.

Indeed, Aeroacustics simulation (CFD simulation) is performed using a mesh of the environment, while a mesh of the vehicle is required to perform NVH simulation (FEA simulation).

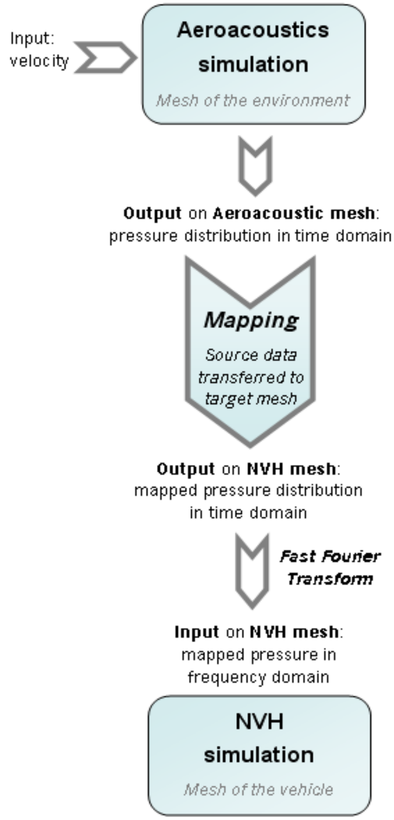

Fig. 4. Simulation Workflow between NVH and Aeroacustics

The meshes are not matching at the common boundary of both simulations, i.e. the outer surface of the vehicle. Therefore, a digital process called "mapping" must be performed. The mapping consists in using a mathematical algorithm (called interpolation) in order to approximate the source model pressure distribution in order to fit with the geometry of the target model. [15][17].

Similarly, the dependency between Forming and Crash simulation is a FE model. The model geometry obtained after forming simulation is used in crash simulation (the initial CAD model can be different in thickness for example). On the other hand, the material properties are modified after forming simulation (compared to initial CAD model which contains classical material properties).

The outcome of such CAE networks increases the quality of simulation as the inputs used to perform NVH or Crash are more in details. Moreover, by CAE networking actual data can be used as compare to prototype results that are performed mostly at the last phase of development process. The CAE network eliminated traditional simplified load cases for which data is imported from prototype testing. Due to the confidentiality and validating the results on various use cases, qualitative results are not mentioned in this paper.

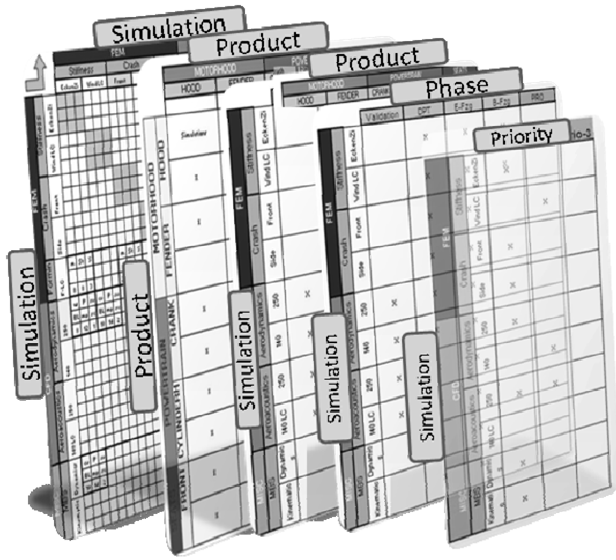

Fig. 5. Generic Relation Matrices (GRM)

Developing of CAE network leads to generic matrices and there are 5 types of relations matrices used in this methodology. Types are:

1. Simulation - Simulation (e.g. Aerodynamics and Stiffness have pressure dependency)
2. Product – Product (e.g. Motor and Motorhood have temperature dependency)
3. Simulation – Product (e.g. Aerodynamics and Exterior Body have decision variable)
4. Simulation - Phase (e.g. Crash – Later Phase also a decision variable)
5. Simulation – Priority

Simulation – Simulation relation matrix is 100% generic matrix. Simulation -- Product and Product - Product relation matrix is generic with respect to automobile industry. The rest of matrices are dependent on companies' requirements.

The most challenging part of this research is the description of a particular process from a GRM shown in Figure 5. An algorithm defines the reduction of GRM volume to a particular product, phase and priority. The first factor which influences the process is the type of product: for example, the interior vehicle's parts do not need to undergo Aerodynamic analysis; as a result, the GRM volume is directly reduced. The next factor is vehicle development phase, e.g. in the early phases of vehicle development, Fatigue analysis plays no role. Similarly, the priority of the digital validation is also important, e.g. in automotive industry. An abstract view of CAE process is shown in Figure 6, the CAE methods are parallel and divided into their activities, dependencies and time line. Different sign modes are used to illustrate the various dependencies and rating simulation quality.

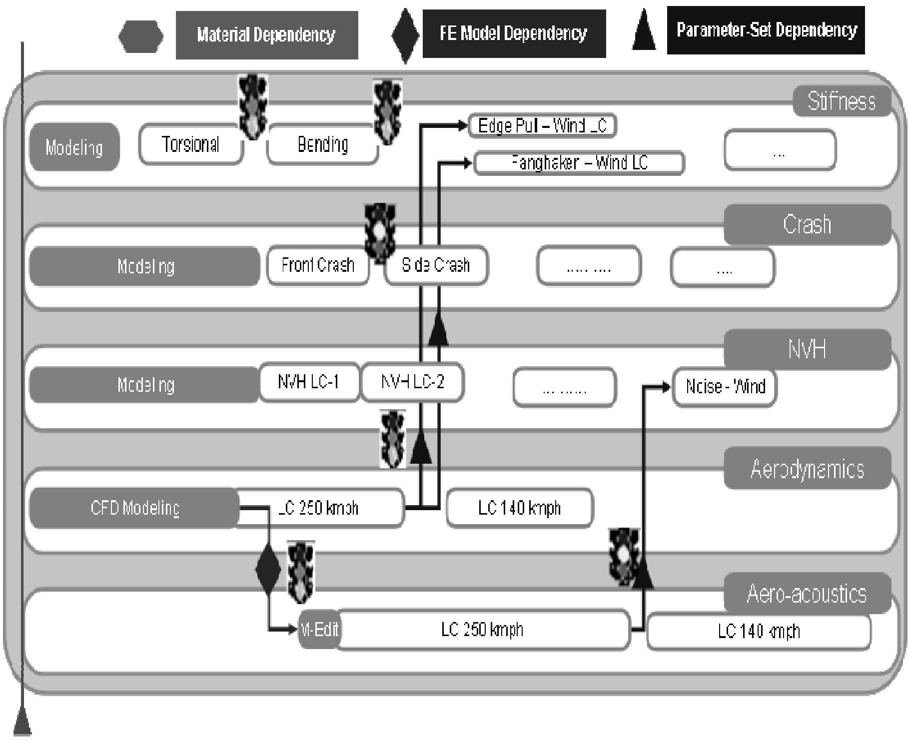

Fig. 6. CAE process derived from the methodology

3.2 Technical Facets and Implementation of the Methodology

Technical facets of the methodology are used case diagrams which describe the role of each user, factors to connect the methodology to simulation data management, developing the generic relation matrices and connect the various users in one platform. After continuous discussion with CAE experts and CAE researcher on the new methodology, following common queries towards the conceptual solution figure out:

- How to create the Generic Relation Matrices (GRM)?
- Who will be the creator and user of Generic Relation Matrices (GRM)?
- How to generate the process from the Generic Relation Matrices (GRM)?
- How it is linked to Simulation Data Management and Functional Requirement?

Answers of the queries are portrayed in Figure 7 CAE Networking and Process (CAE-ProNet) which represents whole process of CAE networking.

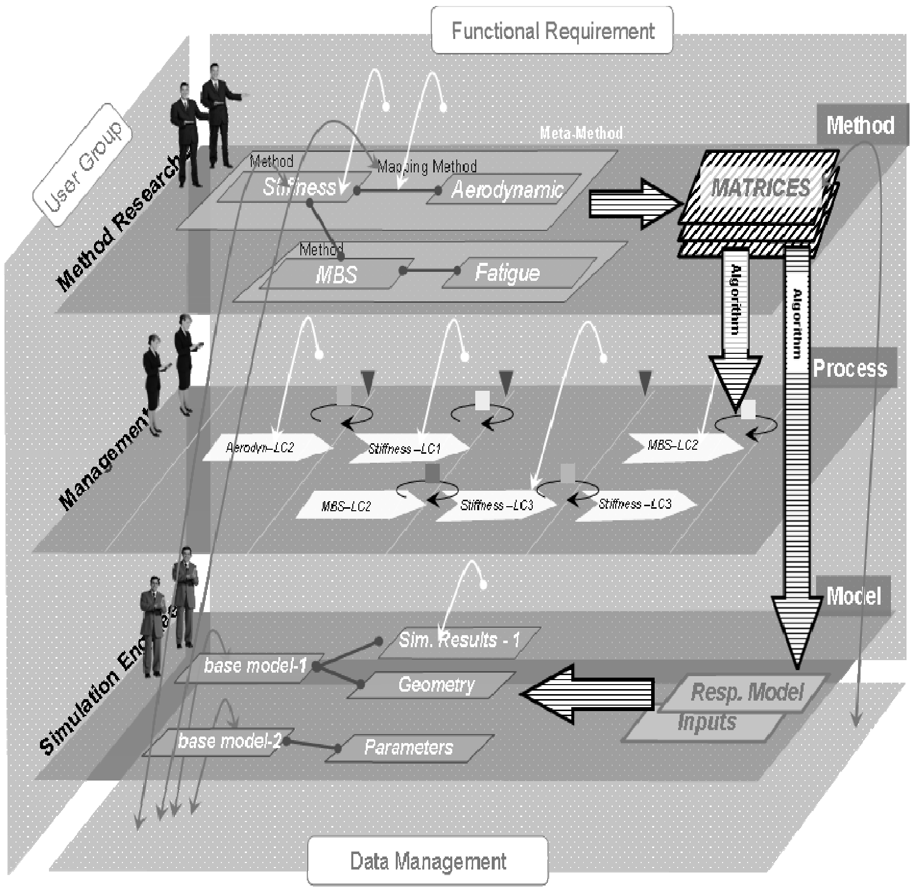

Fig. 7. CAE ProNet Summary Picture

There are three major actors which are responsible for maintaining and developing CAE Network and Process (CAE ProNet). They are method researchers (also known as method engineers), process managers and simulation engineers. The method researchers collect the theoretical information of the simulations, analyze them and define simulation methods and mapping methods for dependent inputs. Validation relation factors are stored in matrices and finally saved in simulation data management. An algorithm is devised to describe the CAE process from generic validation matrices according to the process requirement controlled by process managers. The bottom layer shows the role of the simulation engineers in the CAE process. They receive input data with quality information according to defined CAE process.

As referred from figure 7 that is a huge amount of information being exchanged among described domains and within each domain. The CAE ProNet admin is responsible for the data exchange among given domains. The use case diagram (Figure 8) which is build to develop an application based of activities of each actor are shown below.

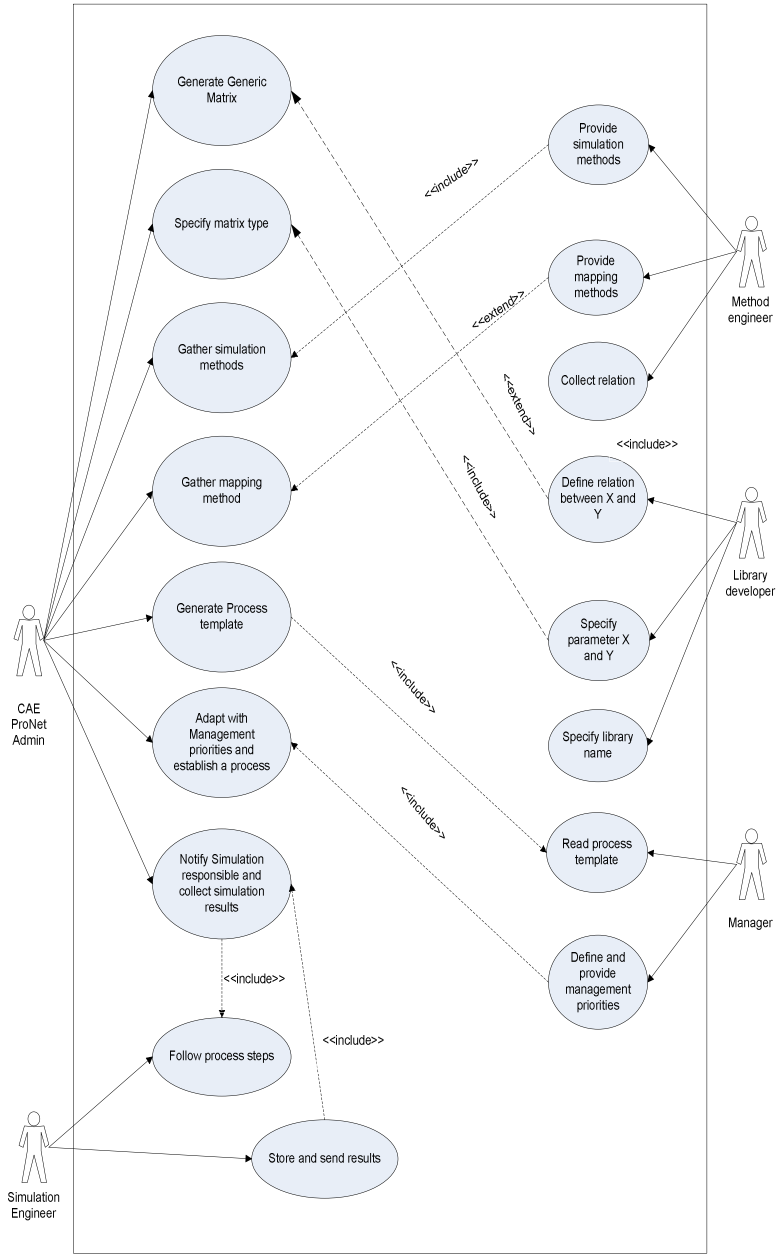

Fig. 8. CAE ProNet - Use case Diagram

3.3 Added Value from the New Methodology

The benefits of the research carried out are as follows:

- Better Simulation Quality:

By means of CAE Networking, inputs received to simulation engineers are in detailed form as compared to simplified, assumption or component based simulation. Thus the results carried out by computational means are better approximation and closer to the real results.

- Better System Organization:

Complexity of simulations and its processes is well managed. The system responsible get an overview about all relevant validations, dependencies, mapping and the process related to the considered system. Effective management decision during the development phases for the dynamic changes.

- Reducing dependencies on Hardware Prototypes:

The methodology results in constructing CAE network which assists dependent simulation to use the digital results of its dependent simulation. Thereby, it reduced the dependency on Hardware prototypes.

- Reducing redundant mapping tool:

One of the aftermaths of CAE network is the reduction of redundant mapping tools.

4 Related Work

In the COREPRO project (funded by Uni-Ulm and Daimler AG), fundamental requirements for the IT support of development processes is elaborated. In particular, every subcomponent of the product has related processes that have to be mapped to the overall development process structure and to be synchronized according to the dependencies between the subcomponents. COREPRO is to utilize this information in order to enable the automated coordination data-driven (i.e., product-driven) process structures. The idea is to support the full process life cycle comprising modeling, enactment and change of process structure. The motivation of this project is to link the product dependencies which are similar to this research as linking of CAE dependencies is the focus of this research. [12].

Dissertation by Uwe Gühl on “Design and realization of a modular architecture for a vehicle draft system”. It is shown that, especially in the early stage of the car development, there is the possibility to create rapidly car concepts using a modeling tool and to validate these models using simulation tools. In order to address these issues a modular architecture concept is introduced to integrate simulation programs. In a connected relational database the car concept data and configuration data are managed. The project focus was on early stages of car development process and on the function of the product. Other similar projects are objected to CAD-CAE networking [13] [14].

5 Conclusion and Further Approach

This paper portraits technical facets of a new methodology to develop the CAE network and then driving an explicit product, development phase and priority oriented CAE process. The CAE network by means of generic relation matrices helps every industry to reduce the complexity of managing simulation data. The CAE process helps to improve quality of digital validation and simultaneously reduces the time-to-market by decreasing the dependencies on hardware prototype. The further approaches are to develop relation matrices between product to product with respect to simulation dependencies and devising an algorithm that describes an explicit process from proposed CAE network.

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The Defect Detection of Fibre Boards Gluing System Based on TRIZ

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Abstract. Defect signal is always a problem that interferes with the operation of fibre board gluing control system. Complex problem analysis and solving are an important evolutionary direction of TRIZ. This research creates a defect diagnosis methodology by synthesizing the Theory of Inventive Problem Solving (TRIZ) and a Possibilistic C-Means (PCM) improved Support Vector Data Description (SVDD) method. Applied TRIZ to identify core root causes and confirm contradictions to classify the system defect. A complex problem solving model integrating SVDD and PCM in TRIZ frame is put forward, a case shows the application of this model.

Keywords: Theory of inventive problem solving (TRIZ), 40 Inventive Principles, defect diagnosis, support vector data description.

1 Introduction

Theory of Inventive Problem Solving (TRIZ in its Russian abbreviation) is an analytical approach to creative engineering. It has been developed in the former Soviet Union by Genrich Altshuller. TRIZ is an algorithmic methodology which helps break psychological inertia in problem solving. It also provides engineers with powerful algorithmic approaches to formulate, analyze, and solve complex engineering problems, as well as to use objective Laws of Evolution of Technological Systems for directed development of next generation products and processes. The main postulate of TRIZ is as follows: Evolution of engineering systems is not a random process, but is governed by certain objective laws. Altshuller formulated eight laws of evolution of engineering systems. These laws can be utilized for conscious engineering system development briefly described below. Altshuller analyzed about 400,000 invention descriptions from different fields of engineering. The most effective solutions were selected and examined to reveal the objective laws (trends) of evolution of engineering systems. The evaluation of the solution's effectiveness was based on the concept of engineering contradiction: A problem becomes a creative one when an attempt to improve system's parameters by conventional means leads to deterioration of other parameters generates an engineering contradiction[1][2].

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TRIZ was born as a problem-solving tool based on a systemic view of the technological world. The primary idea behind TRIZ approach to solving problems is that information about a specific problem must be first generalized, a solution concept has to be generated, and then the concept should be specialized in terms of a feasible solution. Traditional problem-solving methods aim to find a specific solution to a specific problem often using brainstorming or trial and error processes. In contrast, TRIZ translates the specific problem into an abstract problem or model of the problem and then to an abstract solution or model of the solution. Figure 1 depicts this strategy.

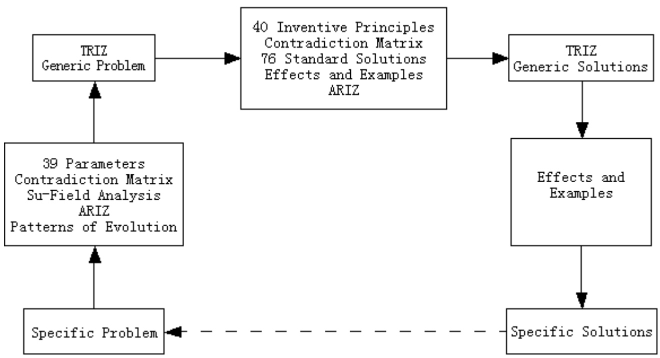

Fig. 1. TRIZ model for problem solving

TRIZ has been successfully applied in a number of industries to structure the innovation process. Mixing and supplying glue technology of particleboard is one of the key technologies on particleboard production line, although the investment of the entire section of all investment in whole line just accounted for 3% to 6%, but it makes significant influence on whole line production. In the same process condition, excessive glue application will lead to high moisture content of particleboard, which can easily result in bubbling phenomenon and increased production cost at the same time; if glue application is insufficient, the plasticity of particle will be small, the bending strength and plane tensile strength of particleboard will decrease with the reduction of glue application, which lead to the decline in the quality or substandard products.

Gluing is one of the key steps in the manufacture of fibre board, and gluing control system directly affects product quality and costs. Improper proportion of the glue will lead to the degradation of the physical properties of fibre boards. In the gluing procedure, the quantity of glue should be kept with the change of fibre, and previous researches have proposed a series of optimal algorithms to control the non-linear model of gluing system, but the defect signals, which always interferes the fibreboard gluing control system, is ignored. Existing innovation methods in control field are mainly genetic algorithm or fuzzy-PID. In this paper, a systematic approach to build a method integrated TRIZ and SVDD for gluing system control strategies was proposed.

2 Background of TRIZ

Theory of Inventive Problem Solving (TRIZ in its Russian abbreviation) has been developed in the former Soviet Union by Genrich Altshuller, starting in the fifties. The main postulate of TRIZ is as follows: Evolution of engineering systems is not a random process, but is governed by certain objective laws. Altshuller analyzed about 400,000 invention descriptions from different fields of engineering.

The difference between control strategy and numerous patents on which TRIZ was based makes some inventive principles, universal parameters and general solutions in TRIZ hard to get correspondences in control theories directly. Applying TRIZ into an integrated control system should include some basic parts, for example, laws and routes of control strategies evolution, levels of invention of control strategies, contradictions and their types in control strategy design problems.

2.1 The Ideal Design with No Harmful Functions

2.1.1 Technical System Describe

Gluing is the key process for the particleboard production, the adhesive which distributed evenly in the debris on the surface will have a direct impact on the quality of the finished product. We considered the factors impacting on the particleboard quality in the process of system analysis and got the sub-system and the super-system. We defined the Operational Zone(OZ) and the Operational Time(OT) then using the three-dimension analysis to get the Route Course(RC). To control the flow of the glue and the rotate speed of the pump according to the weight of the fibre.

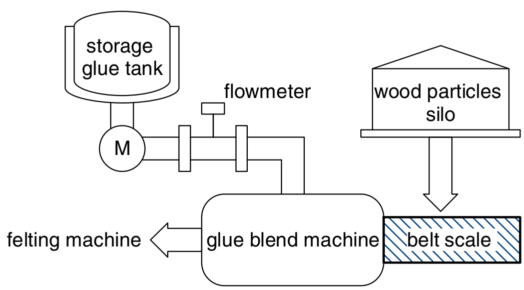

Fig. 2. Particleboard supplying glue system

2.1.2 Definition of Glue Dosing System

A system can be thought of as "a group of interacting, interrelated, and interdependent components that form a complex and united whole. Systems are almost always defined with respect to a specific purpose within a larger system. The system of supplying glue section in particleboard production line is composed of a glue storage tank, measuring devices, glue pumps, pipes and other components, divided into surface and core layer applying glue, with the same process and the symmetry structure. To solve the existed problem, the following supersystem in which the system resides were considered, such as air, the shape of flake, the pipelines and the density of the flake etc.

2.2 Functional Analysis of the Glue Dosing System

When analyzing this case, the first step was to describe the components in and around the system; the second detailing the useful relationships between each pair of components; the third then describing the negative (harmful, insufficient, missing or excessive) function present in the system.

The primary useful function of the glue dosing system is to measure flow accurately. Through the proportioned glue is stored in glue storage tank in accordance with the timing, supplying glue process is that shavings is sprayed by the corresponding glue mixture which is pumped from the two glue storage tank separately according to the weight of surface particle (thin stuff)and the weight of core layer and particle weight (coarse material), the particles is transported by Electronic belt scale, particle flow is measured precisely by rotary encoder, and glue content is measured by electromagnetic flow transmitter and load sensors ,and then supplying glue steadily is realized though the method that using frequency converter to control the supplying glue pump.

2.2.1 Define the System Boundaries and Environment

TRIZ is a scientific methodology for defining, analyzing and formulating solutions to difficult problems usually of a technical nature. This research includes other systems nearby the supersystem: forming machine, hot press and sanding machine.

2.2.2 Conditions around the System and Its Supersystem

Mixing and supplying glue system is a complex system with the characteristics that great time-delay, great inertia, multiple disturbance、nonlinear and time variation, and these characteristics make supplying control more difficult.

2.3 Define Available Resources

Since glue cost is high and the supplying glue control has a direct impact on hot pressing results of particleboard, the large time delay characteristic of supplying glue system affects product quality seriously. In addition, as the factors that electromagnetic interference, pressure variation inside and outside the pipe、mutations of shavings flow, failure shutdown etc exist in the control system during the supplying glue process, the traditional PID controller is difficult to achieve the required control quality of the system and manual intervention is often required.

Resources refer to anything in or around a system which is not being used to its maximum potential. TRIZ looks for resources of innovation in the system itself not in the individuals or the organization surrounding it, so we can manage and guide the processes of value maximizing by problem solving. Any physical object with mass or that occupies space and that potentially can be used to improve a system calls substances. Includes Substance Resources: glue, flake, air etc, Space Resources: the length of the pipe, Time Resources: the time of flowing through the pipe, Information Resources: the flake’s shape and density; Fields is defined as the energy needed for the interaction of substances within a system that can potentially be used to improve the system. Field resources: Chemical Field, electrical Field, mechanical Field.

2.4 The Contradiction in Technical System as a Basis of Innovation

The evaluation of the solutions' effectiveness was based on the concept of engineer contradiction: A problem becomes a creative one when an attempt to improve system's parameters by conventional means leads to deterioration of other parameters.

In control system, requirements to rise time and accuracy usually can’t be satisfied simultaneously with a single control strategy. It would compose a technical contradiction and physical contradiction. From the standpoint of TRIZ, solving a problem means overcoming this contradiction, or satisfying all conflicting requirements. 40 inventive principles (classes) of TRIZ are one of the less widely used innovation tools. Its have been the basis of the study for innovations in mechanism system. TRIZ researchers have configured a tool called a Contradiction Matrix. The contradiction table is a 39╳39 matrix of all the characteristics on the rows and columns. To use it, first look up the character you wish to improve and go to its appropriate row. Next, locate the column of the characteristic that degrades as a result. Where the row and column intersect are numbers that correspond to the 40 inventive principles.

Table 1. Contradiction matrix table

	Characteristic that is getting worse			
Characteristic that is getting improved	Engineering Parameters	35	36	37
		Adaptability or Versatility	Device Complexity	Difficulty of Detecting
	23 Loss of Substance			
	24 Loss of Information			
	25 Waste of Time			
	26 Amount of Substance		3,13 27,10	
	27 Reliability			
	28 Accuracyof Measurement			

The next step is to identify the standard and/or proposed contradictions in the case. In the supplying glue system, we found a main contradiction for the Macro-level and Micro-level that we wish to improve from the row 26 amount of substance, thus the undesired result ——the characteristic that degrades as a result of improving the above feature, the column 36 device complexity. From the standpoint of TRIZ, solving a problem means overcoming this contradiction, or satisfying all conflicting requirements. Based on the matrix they would obtain the solutions as 3 Local Conditions principle, 13 Inversion principle, 27 Disposable Object principle, 10 Preliminary Action principle. With the sequence given in the descending order of usage.

Among the four recommended principles, number 10 (preliminary action) provided feasible ideas to realize our IFR(Ideal Final Result, the evolutionary end-point for a system). Problems that contain contradictions or conflicts can be solved one of two ways: either by making tradeoffs or by stating the objectives in the form of a contradiction and then solving the contradiction. Usually contradictions are resolved though trade-offs by finding some compromise between the two requirements. This results in a solution that does not fully satisfy either element. TRIZ, on the other hand, does not attempt to make trade-offs between two requirements in features or functions. Ideality is typically defined as benefits divides by cost and harm.

The last step in the analysis is to identify the principles used in solving the problem and how they were used. Principle 10 preliminary action——Arrange objects so they can go into action in a timely matter and from a convenient position, place each part of the object under conditions most favorable for its operation. Perform before it is needed.

Increasing system dynamism and controllability allows functions to be performed with greater flexibility or variety. We apply the cascade control system design based on predictor in advance. The Smith Predictor will be employed to the control system. Most of the principles suggested from the matrix match the concepts used in the actual solution of the problem.

The paper also considered solving the problem using a substance resource and field. Substance-Field analysis is a TRIZ analytical tool for building functional models for problems related to existing or new technological systems. Substances may be materials, tools, parts, people or environments. Fields may be mechanical, thermal, chemical, electrical or magnetic. 5 classes of 76 standard solutions are offered. According to su-field concept, model of the problem can be represented by S_1 (pump). To control S_1, a pair F-S_2 should be introduced into the system. S_2 is to transform F into mechanical field (force) which would act on S_1.Due to ineffectiveness of mechanical F, it was natural to suggest transition to microlevel which can be realized by use of control using a predictor.

3 The Detailed Steps of Using Multi-classifier by SVDD

3.1 An Overviews on SVDD

SVDD was developed to solve one-class classification problems, and its main idea is to map data points by means of a nonlinear transformation to a high-dimensional feature space. In the feature space it first find the smallest sphere that contains most of the mapped data points in the feature space, and then mapped back to the data space. In the way above the data can be separated into several components, each enclosing a separate cluster of points [10] [11] [12]. SVDD obtains a boundary around the target data set, and this boundary is used to decide whether new objects are target objects or outliers.

The simplest idea of SVDD defines a hyper sphere around the data and the goal is to minimize the volume of the sphere. The minimum enclosing sphere S is characterized by its center a and radius R which keeps all the training objects inside its boundary.

The structural error of SVDD is as follows:

$$F(R,a) = R^2 \tag{1}$$

$$\text{Subject to } \|x_i - a\|^2 \le R^2 \tag{2}$$

To allow for the possibility of some samples falling outside of the sphere, we can relax the constraints by introducing slack variables ξ_i, and then the minimization problem can be turned into (3):

$$F(R,a) = R^2 + c\sum \xi_i \tag{3}$$

$$\text{Subject to} \quad \|x_i - a\|^2 \le R^2 + \xi_i, \quad \xi_i \ge 0 \tag{4}$$

Where a is the center of the minimum enclosing sphere S, ξ_i are slack variables allowing for soft boundaries, the parameter c controls the trade-off between errors and the volume of the description. To solve this problem, the Lagrange multipliers are introduced:

$$\begin{aligned} L(R,a,\alpha_i,\beta_i) = R^2 + c\sum \xi_i - \\ \sum (R^2 + \xi_i - \|x_i - a\|^2 \alpha_i - \sum \beta_i \xi_i) \end{aligned} \tag{5}$$

By Using the Lagrange multiplier method, the above constrained quadratic optimization problem can be formulated as the Wolfe dual form. To solve the partial derivatives of L about R, a and ξ_i we set their derivative value to zero, and then get (6) (7) (8):

$$\frac{\partial L}{\partial R} = 2R(1 - \sum \alpha_i) = 0 \Rightarrow \sum \alpha_i = 1 \tag{6}$$

$$\frac{\partial L}{\partial a} = 2\sum \alpha_i (x_i - a) = 0 \Rightarrow a = \sum \alpha_i x_i \tag{7}$$

$$\frac{\partial L}{\partial \xi_i} = c - \alpha_i - \beta_i = 0 \Rightarrow c = \alpha_i + \beta_i \tag{8}$$

Taking (6)–(8) into (5), we obtain the dual formulation

$$L = \sum \alpha_i (x_i \cdot x_i) - \sum \alpha_i \alpha_j (x_i \cdot x_j) \tag{9}$$

$$\text{Subject to} \quad 0 \le \alpha_i \le c\,, \ \sum \alpha_i = 1$$

The maximization of (9) gives a set $\{\alpha_i\}$. Objects x_i with α_i are called the support vectors (SVs) of the description. (7) shows that the center a of the sphere S is the linear combination of the support vectors.

To decide whether an object x belongs to the target, the distance from the object x to the center of the sphere has to be calculated. The object x is accepted as a target when this distance is smaller than or equal to the radius; otherwise it is beyond the target. Hence, the following condition has to be verified. R is the distance from the center of the sphere a to any support vector x_i on the boundary.

It is worth noting that all ϕ mappings used in the SV method occur in the form of inner products. This allows us to define a kernel function K, and the nonlinear SVDD can be constructed using only the kernel (10), without needing to know the mapping ϕ explicitly.

$$K(x_i \cdot x_j) = (\phi(x_i) \cdot \phi(x_j)) \tag{10}$$

3.2 Constructing Multi-classifier Based on SVDD

We can adopt one-against-all method to construct multi-classifier algorithm [13]. Given a set of l labeled training samples $z = \{(x_i, y_i)\}_{i=1}^{l}$ with a label space $y = \{1, 2, ...c\}$, we first partition the training samples into c disjoint subsets $\{D_k\}_{k=1}^{c}$, according to their output classes, each given as $D_k = \{(x_i, y_i) | y_i = k\}$. For each subset D_k, an SVDD is trained by using D_k as the target class and the remaining subsets as the negative samples. This leads to c optimal hyper spheres, with each center denoted as a_i. Using one-against-all method, the label of an input sample is simply predicted as the class where its nearest-neighbor center belongs to, which is given as

$$y_z(x) = \arg \min_{i=1,2,...c} \|\phi(x) - a_i\| \tag{11}$$

4 Possibilistic C-Means Algorithm

The idea of PCM algorithm was originally proposed to overcome the relative membership problem for fuzzy c-means algorithm, and the algorithm has shown the excellent ability to deal with noises and outliers samples. Its basic idea is to relax the constraint and propose a possibilistic method for clustering by minimizing the following object function:

$$J(U,V) = \sum_{i=1}^{c} \sum_{k=1}^{n} u_{ik}^{m} \|x_k - v_i\|^2 + \sum_{i=1}^{c} \eta_i \sum_{k=1}^{n} (1 - u_{ik})^m \tag{12}$$

where c is the number of clusters, n is the number of data points, u_{ik} is the membership of x_k in class i, m is the quantity controlling clustering fuzziness, v is the set of cluster centers, and η_i are suitable positive numbers.

First we demand that the distances from data points to the prototypes be as low as possible, and then we force the u_{ik} to be as large as possible, thus avoiding the trivial solution. We can use kernel technique to generate kernel PCM.

5 Example for the Application of the Proposed Method

5.1 The Defect Problem of Fibre Board Gluing System

The structure of fibre board gluing system is shown in figure3, which is made up of 3 parts, fibre supply device, glue supply device, and blender.

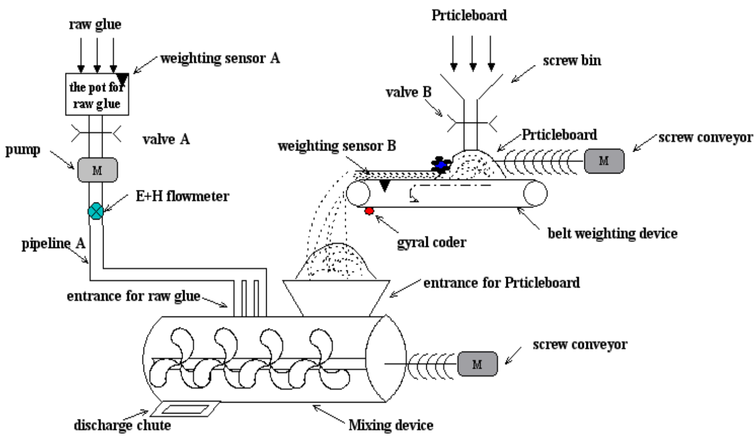

Fig. 3. The structure of fibre board gluing system

In the gluing system, there are usually 6 types of defects. The types are the gluing system is out of control, glue bump does not work well, the glue supply pipeline is blocked, the fibre supply screw is malfunctioned, the blender is blocked, and the flux control of fibre supply does not work normally. In order to map problems to the solution domain, we define the 6 defects as $R_1, R_2, R_3, R_4, R_5, R_6$ respectively, and each symbol matches one type of defect. The symbols and the types of defects are shown in Table 2. Now, TRIZ is used to deal with the above mentioned problem. Accordingly, rich information and insight for idea generation can be achieved by TRIZ technique. When engineers have sufficient training, experience, and practice, they will exploit the potential of TRIZ and search for feasible solutions effectively based on the knowledge base of TRIZ.

Table 2. The types of defect

symbol	The type of defect
R1	gluing control system
R2	Glue bump
R3	Block of glue supply pipeline
R4	The screw of fibre supply
R5	Block of the blender
R6	Flux control of fibre supply

From some workers with experiences with gluing system, we conclude some parameters that can be measured by some sensors. When the defect happens, these parameters change, so we employ these parameters to identify the defect signals. Actually, there are 5 parameters expressing the defect types, they are the glue quantity in the storage which is measured by weight senor, the glue flux in the pipeline measured by E+H, the fibre quantity detected by weight sensor, and the rotation speed of glue bump and the blender respectively detected by knotmeter. We define the measured data identifying the defect types as $F1$, $F2$, $F3$, $F4$, $F5$. Table 3 gives the matching relationship between the symbol and physical data measured by different sensors.

Table 3. Physical data recognizing the defect types

symbol	Physical data	Senor type
F1	The glue quantity in storage	Weight sensor A
F2	The flux in glue pipeline	E+H
F3	The fibre quantity	Weight sensor B
F4	Rotating speed of glue bump	knotmeter
F5	Rotating speed of the blender	knotmeter

5.2 Apply the SVDD Method to Find Solutions

From actual production, we collect 300 data and divide them into 2 groups, the first group containing 150 data is used as training examples, and the other one is used as testing examples. We adopt the Gaussian function as a kernel function in PCM algorithms for improving SVDD, which is $K(x_i, x_j) = \exp(-\|x_i - x_j\|^2 / \sigma^2)$. When we use the Gaussian function as the kernel function, we get $K(x, x) = 1$ and $\|\phi(x_k) - \phi(v_i)\|^2 = 2 - 2K(x_k, v_i)$.

Table 4 shows the defect diagnosis accuracy rate comparison of fibre gluing system between original SVDD multi-classifier and the improving SVDD multi-classifier by using PCM. We can see, by using our proposed new algorithm, the performance of the resulting classifier is improved significantly, and the accuracy is up to 97% which is much better than that of the original SVDD multi-classifier. We can conclude that PCM help SVDD multi-classifier overcome the negative effects of the outliers and noise, and the robustness and accuracy improved.

Table 4. The accuracy comparison of the 2 multi-classifier

Method	Accuracy rate
Original SVDD	82%
PCM based SVDD	97%

Table 5. Status analysis of the gluing control system

Inputs					output
F1	F2	F3	F4	F5	
0.60	0.75	0.67	0.48	0.5	normal
0.66	0.75	0.22	0.78	0.5	R6
0.67	0.90	0.85	0.48	0.5	R2
0.65	0.74	0.64	0.48	0.5	normal

Table 5 shows some defect diagnosis results, which is consistent with the actual status. When we get the physical data from the sensors respectively, and then input them into the PCM improved SVDD method, we can get the status of fibre gluing control system. The input section is the physical data which has 5 parameters, and the output section is the status of the fibre gluing system and has 6 statuses which include 5 defect statuses plus 1 normal. Because the defect diagnosis serving in the fibre gluing system gives signals to the control system, the stability of the control system based TRIZ is enhanced, and the production quality is improved.

6 Conclusions

This paper describes work to integrate SVDD and TRIZ techniques to produce a method combining the best features of both. The paper also describes the research on the defect diagnosis method of the fibreboard gluing control system. Since TRIZ can expedite design process and help designer solve problems in a creative mode, the paper analyzed the supplying glue system problem, formulated the mini-problem and defined the conflicting elements, got the inventive principle to solve the contradict problem.

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Computer-Aided Problem Solving - Part 1: Objectives, Approaches, Opportunities

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Abstract. Among the different aims and scopes of Computer-Aided Innovation (CAI) systems a relevant topic is the support of inventive problem solving tasks. The paper presents the research activity developed by the authors in this domain, encompassing the review of the distinctive features of problems encountered by designers and the common approaches employed to overcome them. A further thread of the investigation carried out in this paper concerns the limitations of computer-based approaches exploiting acknowledged models for problem solving. Downstream of the performed analysis the authors highlight the requirements that a novel CAI application should fulfil, supporting the opportunities for building a dialogue-based system.

Keywords: Computer-Aided Innovation, inventive problem solving, conceptual design, dialogue-based system.

1 Introduction

CAD/CAE systems have reached considerable performances in terms of rapidly carrying out routine tasks, allowing to successfully perform detail design activities. On the contrary, their development has not so far concerned the ability to support the early stages of the design process, such as conceptual design, resulting in limited functionalities to enhance product development cycles. Such design phases, in which designers' creativity and inventiveness are primarily exploited, play a crucial role for the success of the products in the marketplace.

Thus, considering companies' double goal of delivering innovative products and reducing the time to market, CAD/CAE systems have consistently focused just on the second objective, by speeding up the processes concerning detail design. Indeed, starting from the CAD-CAM systems which spread since the '80s, computer means supporting the product development cycle have progressively extended their domain of application, also acquiring virtual prototyping capabilities. Product models correspondingly extended the detail level of representation, in order to allow simplified simulation and testing. In the last decade, CAD/CAE systems have been integrated into PLM (Product Lifecycle Management), further extending their domain

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of application, but still missing to support the earlier stages of design. Figure 1 represents the domains of application of these systems with respect to the phases of product development and the abstraction level of the adopted product models.

Thus, the aforementioned scope of shortening the lead times has resulted in less accurate initial design phases, with poor support to problem investigation, function analysis, solutions generation and exploration [1], thus shrinking innovation opportunities.

Computer-Aided Innovation (CAI) systems emerged for suitably assisting the conceptual design phase. As depicted in figure 1, the borders of CAI systems domain are still fuzzy, but their capability to support problem solving seems to be a core element on which the scientific community agrees.

Within this context, the authors' research aims at developing an original computer application viable to overcome the deficiencies of CAD/CAE tools with respect to conceptual design and the limitations of CAI systems in exploiting designers' skills, creativity and intangible knowledge.

Due to space limitations, the recalled subjects are treated in two separate and complementary manuscripts: the current one deals with the identification of the requirements to be fulfilled and the tasks to be performed by a CAI problem solving tool. With reference to these findings, the second paper illustrates a dialogue-based algorithm, embedding the TRIZ logic, tailored for people without any background in problem solving methods. By aiding the investigation of a technical problem, such algorithm represents a first module for a complete CAI system to support the conceptual design phase.

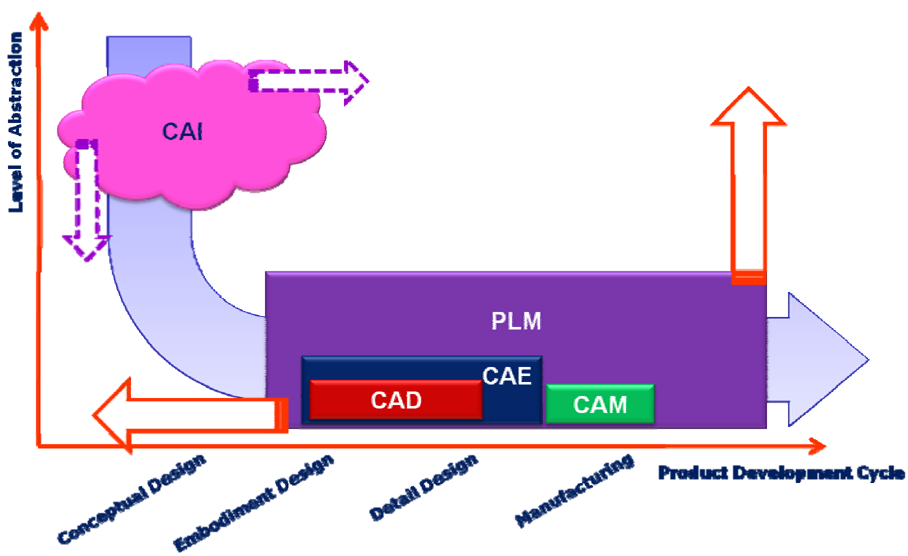

Fig. 1. Current domains of application of PLM and CAI systems within the product cycle and level of abstraction of the corresponding product models. The arrows represent the expected trends of evolution.

According to these premises, this paper firstly performs a review of problems typically encountered by designers (Section 2); then, problem solving approaches and computer-based approaches for problem solving are discussed, focusing on the role played by knowledge in the design context (Section 3). The investigation within innovation tools in design subsequently focuses on the opportunities represented by dialogue-based systems and the employment of natural language (Section 4). The outcomes of the whole research are finally summarized in Section 5.

2 Types of Problems

In the literature there is a plenty of definitions of the term "invention": among the others, for the scopes of the present paper, it is useful to mention the followings:

- Patent Law recognizes as inventive a technical solution that is useful, novel (no single prior art reference shows the identical development), and unobvious to a person "skilled in the art";
- Cavallucci et al. associate the concept of invention to the transfer of knowledge between different fields of application; in [2] it is claimed that "Inventive R&D requires the use of knowledge or know how from a substantially different technical domain".

The first definition is here assumed as the reference to identify an invention, since it is more universally accepted, at least in the industrial world. It relates to the usefulness of an invention, meaning that the technical solution is addressed to satisfy a need, which implies to solve an existing and acknowledged problem. Nevertheless, the second definition is relevant for a class of "inventive problems" and requires a specific solving approach.

Technical problems can be indeed distinguished between inventive and non-inventive, whereas demands and cognitive processes make the differences in this classification. Non-inventive problems don't require any inventive step, thus relate to situations where the desired outcome can be achieved just by means of an optimal adjustment of system parameters. On the contrary, inventive problems are characterized by at least two conflicting requirements that cannot be satisfied by choosing the optimized values for system parameters. Thus, inventive problems require an inventive solution, which means that it's necessary to solve a contradiction in order to produce a useful, novel and unobvious answer to an emerging demand.

From another point of view "difficult problems", according to Funke and Fresch [3], have at least one of four specific characteristics that make them harder to solve than "easy problems":

- Intransparency, due to the ill-definition of the problem itself, some elements required to achieve the solution are not known;
- Complexity, due to the great number of parameters of the technical system(s) and their mutual connections;
- Dynamics, due to either time-dependent characteristics of relevant features, or to the need of achieving the solution under time pressure;
- Polytely, which means that the problem is characterized by multiple, non-compatible goals.

From a different perspective, it is possible to distinguish between typical and non-typical problems. Both problems can be approached by means of rules and procedures, but the second ones cannot be solved just by means of such methods; their solution requires the support of knowledge provided by the problem solver and the available informational support. An example of typical problem is the calculation of the roots of an equation of the n-th degree: it's required just to know the appropriate formulas (available for equation from first to 4th degree) or a method (e.g. Ruffini-Horner) that provides the desired approximation of their values. On the contrary, when the problem is non-typical, even if some solution path is provided, the solution cannot be entrusted just to the method itself. This problem solving process requires elements of knowledge that reside outside the boundaries of the method and its language. To get to the desired outcome it's necessary to leverage personal knowledge as well as personal wisdom.

Finally, Simon, in [4], explores the distinction between a well-structured problem (WSP) and an ill-structured problem (ISP): "… a problem may be regarded as well structured to the extent that it has some or all the following characteristics:

1. There is a definite criterion for testing any proposed solution, and a mechanizable process for applying the criterion;
2. There is at least one problem space in which can be represented the initial problem state, the goal state, and all other states that may be reached, or considered, in the course of attempting a solution of the problem;
3. Attainable state changes (legal moves) can be represented in a problem space, as transitions from given states to the states directly attainable from them (…);
4. Any knowledge that the problem solver can acquire about the problem can be represented in one or more problem spaces;
5. If the actual problem involves acting upon the external world, then the definition of state changes and of the effects upon the state of applying any operator reflect with complete accuracy in one or more problem spaces the laws (laws of nature) that govern the external world;
6. All of these conditions hold in the strong sense that the basic processes postulated require only practicable amounts of computation, and the information postulated is effectively available to the processes – i.e., available with the help of only practicable amount of search.…"

His description is founded, by his own admission, on a set of features that problems must have in order to be considered as WSP, since it's impossible to provide a formal definition. The class of ISP, indeed, must be considered as a residual of the one related to WSP.

Given these commonly faced situations, Computer-Aided Innovation (CAI) systems constitute an emerging technology for assisting the conceptual design phase by supporting the solution of inventive problems, but also improving the efficiency of any problem solving activity arising in an innovation process. A framework for Computer-Aided systems should be thus capable to face and solve:

- inventive problems by the search of conflicting requirements and the identification of features that the technical solution should have;
- difficult problems by both clarifying their definition and prioritizing the objectives;

- non-typical problems by helping the user in retrieving useful data and information from various domains;
- ill-structured problems by organizing the designer's knowledge according to a framework useful for a successful solution.

These objectives are achieved if the framework helps to approach the problem with a structured process that, during the analysis, stimulates the user's knowledge and his/her creative skills. Thus, a problem solving tool should have the capability of assisting the user in the exploitation of his/her competences during the solving process. Moreover, when the solution space depicted by the designer doesn't provide any successful result, the CAI system should drive the user in the widening of its design space by enriching it with external knowledge. Relevant information should be first searched in a close field of application, since also experts not necessarily fully master their own domain; then, the search should be extended to completely different domains of technical knowledge where similar problems have been already solved with success. With the goal of maximizing the efficiency of the innovation process, such an information search must be performed as automatically as possible by the computer system and should require minimal efforts to the designer.

3 Problem Solving

This section introduces some key concepts related to inventive problem solving and conceptual design, with references to approaches, techniques and research insights relevant for the present work.

3.1 Problem Solving Approaches

The emerging demands for better performances, the reduction of resources consumptions and the removal of harmful side effects generate technical problems due to the conflicting nature of these features. Whenever the optimization of the values of such parameters allows to satisfy the design demands within the established constraints, the solution doesn't require any inventive activity. On the contrary, whenever two or more requirements (demands or constraints) appear as non-mutually compatible just by changing the values of the related design parameters, the issue requires a dialectical approach in order to redesign the system. This inventive problem task implies that the new solution (synthesis) must integrate the needed features (thesis and antithesis) after the removal of the causes that prevent their direct implementation. Optimization and trade off could be considered as routine design, while inventive problem solving relates to non-routine design [5].

Non-routine design activity requires a creative contribution for problem solving. The creativity leaps underneath the solving process have been deeply studied since the '70s [6-8] both to understand human thinking and to provide an efficient way to improve the problem solving activity. With a particular emphasis in [4], Simon distinguishes between ill-structured and well-structured problems and observes that the problem solving approach should be the same, regardless of the problem structure. In a recent paper [7], Dorst calls into question the differences claimed by Simon between well-structured and ill-structured problems, also by highlighting that those differences mainly reside in the skills of the problem solver of turning the latter into the former. Therefore, even according to Simon, the designer's subjectivity becomes relevant for the design process, since the greatest part of its creative contribute is addressed in changing the structure of the problem. To this end, particular regard should be given to the problem solver's interpretation of the problem, both taking into account his knowledge and the method he follows. Kruger and Cross [8] recognize four different types of cognitive strategies in design:

1. Problem driven design: the designer focuses closely on the problem at hand and only uses information and knowledge that is strictly needed to solve the problem. The emphasis lies on defining the problem.
2. Solution driven design: the designer focuses on generating solutions, and only gathers information that is needed to further develop a solution. The emphasis lies on generating solutions.
3. Information driven design: the designer focuses on gathering information from external sources, and develops a solution on the basis of this information.
4. Knowledge driven design: the designer focuses on using prior, structured, personal knowledge, and develops a solution on the basis of this knowledge. Only minimal necessary information from external sources is gathered.

The solution, whatever the adopted strategy, must be found by means of the creative leap of the problem solver or even by increasing his/her knowledge by information gathering. Beyond the cognitive aspects, the above strategies are characterized by different approaches to systematize the design process, then it is worth to make a brief distinction between cognitive and systematic features of the problem solving methods.

Cognitive approaches are focused on creative thinking features like analogy, abstraction and references to previous experiences by associations of ideas. Furthermore, they can be used regardless of the technical/industrial domain and the increase of their effectiveness must rely on multidisciplinary working teams composed by creative people. These methods leverage tacit knowledge, stimulate "cross-fertilization" thinking processes and individual creative attitude upon appropriate conditioning techniques [9].

On the other hand, systematic approaches of problem solving are characterized by linear and ordered "step-by-step" procedures that drive the design process. They rely on explicit knowledge such as information and data available in handbooks, patents, and scientific literature. Furthermore, both teams of experts and individuals can use them since the creative attitudes are welcome, but not strictly necessary. One of the greatest restrictions of these methods stands in their limited versatility: they are suitable just for specific kinds of problems and are hard to be generalized for different expertise domains.

Despite many creative process models and techniques might be considered, e.g. those reviewed in [10], the discussion is here limited to four well known problem solving methods because they allow to highlight a complete set of relevant issues for the present research. Let's examine in detail the main features, differences and weak points of two methods mostly based on the cognitive aspects of idea generation (Brainstorming and CBR, Case-Based Reasoning) and two methods relying on systematic procedures for generating a solution (CPS, Constraint Satisfaction Problem and TRIZ, Theory for Inventive Problem Solving).

Brainstorming is a well known method for generating a flood of new ideas: a group of open-minded and creative experts in various domains elicits ideas and thoughts to solve the given problem during sessions, thus triggering off new ideas in the mind of other participants. This method is strongly based on memory stimulation and on the association of ideas from different knowledge domains. Pahl and Beitz [11] suggest the use of such method whenever the design phase comes to a deadlock because of the lack of practical solution concepts and physical principles to be exploited to get the desired outcomes. During a brainstorming session the working team may produce a huge number of ideas even if the greatest part of them is far from being technically or economically feasible. The greatest drawback of this method stands in its implicit trial and error approach: the generated ideas require appropriate validation and the efficiency of the whole innovation process results to be quite poor. Moreover, a brainstorming session intrinsically leverages only the knowledge of the individuals involved in the idea generation.

The aim of Case-Based Reasoning for problem solving is to build a new solution for a given problem by adapting solutions of past cases [12; 13]. This method makes use of cognitive resources with a different approach, since it leverages an archive of successfully solved cases. Despite its cognitive nature, CBR relies on a well structured procedure described by some authors as the “4 R”: “Retrieve, Reuse, Refine and Retain”. During the retrieval phase the knowledge base of successfully solved cases is searched by exploiting an indexing system that summarizes relevant features of the cases themselves. The best solution gets chosen by means of analogy and similarity criteria. The Reuse phase associates the solution of the retrieved case to the new problem, while the refinement phase checks the overall validity of the proposed solution by verifying whether any modifications are required. The retain phase starts whenever the solution has been adapted to the problem: the new case, comprising the initial problem and its solution, becomes part of the knowledge base of the CBR system.

Constraints Satisfaction Problems (CSP) is a method for finding suitable values for variables subjected to constraints on acceptable combinations of values [14]. A CSP model consists of a set of variables, a set of possible values for each variable and a set of constraints the variables must satisfy. Whenever these constraints cannot be completely satisfied, the user has to deal with an over-constrained problem, an optimization problem that requires non-routine design since its solution cannot be achieved by means of values adjustment. Several CSP methods for over-constrained problem are available to solve non-routine design problems such as Constraint hierarchies, Partial CSP and Extending CSP (Probabilistic CSP; Fuzzy CSP; Weighted CSP). All these methods can be classified according to two general strategies:

- those (as Extending CSP, Constraint hierarchies) that allow to state preferences about constraints, choosing the ones to be overridden whenever the problem model is over-constrained. The CSP algorithm tries to solve the problem by satisfying all the constraints; otherwise the solution is searched by satisfying as many constraints as possible, fulfilling all the required or “hard” ones and neglecting the ones marked as preferential or “soft”.

- those (as Partial CSP) that allow to relax the boundary values of variables and constraints whenever an over-constrained problem arises. Nevertheless these methods don't allow the introduction of new variables in the problem model, reducing the space of potential solutions.

As well known by TRIZ practitioners, the theory developed by Altshuller [15] has several models to describe problems, technical systems, solutions and to address the problem solving process, which is systematically driven according to its main classical tool, the Algorithm of Inventive Problem Solving (ARIZ). ARIZ is a step-by-step procedure that integrates all the others TRIZ instruments and brings from the analysis of two contradictory requirements to the synthesis of a new technical system capable of fulfilling such goal. From a formal point of view, this method cannot be considered as completely systematic since "ARIZ is a tool to aid thinking, but it cannot replace thought itself, (...) if the human brain does not use the power of a lifetime's knowledge, a lot of potential associations and images would be neglected. But it is exactly the sparks of imagination that lead humans to produce creative non typical ideas" [16].

The above-described features of these four methods are depicted in Figure 2, 3 and 4 by means of boxes. Each box qualitatively places the method in a two dimensional diagram, where each axis is referred to a specific characteristic. The boxes may have continuous or dashed border meaning, respectively, that the described characteristic is explicitly presented in the reference or has been inferred by the authors of this paper. Whenever a specific feature of a method cannot be certainly classified because of its intrinsic variability the related box gets wider.

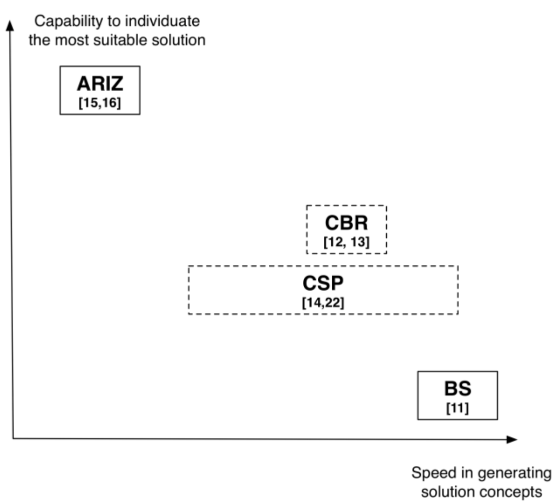

Fig. 2. Brief synthesis of the efficiency of problem solving methods: in this diagram resources of time needed to produce solution concepts are compared to the engineering value of the same concepts

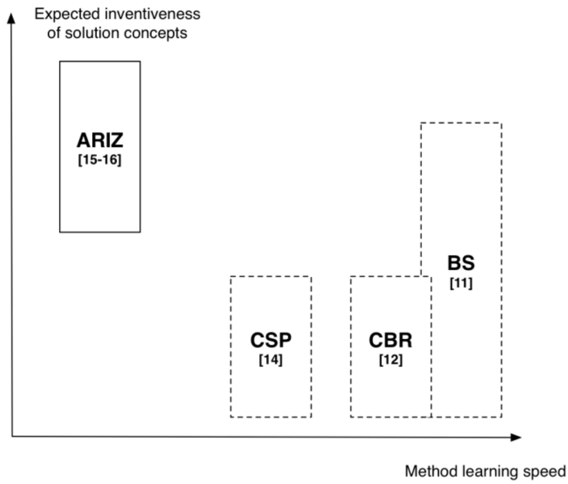

Fig. 3. Qualitative comparison between the capability of solving problems by solution concepts of great inventiveness (whose definition is available in [15]) together with the time required to learn and proficiently use the method itself

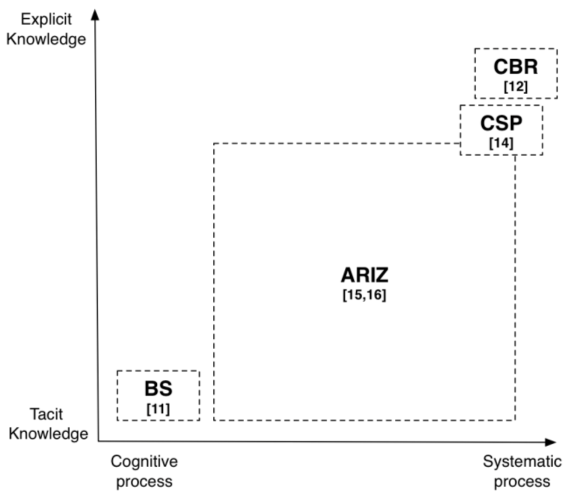

Fig. 4. Problem solving process, differences among the four methods. Cognitive processes leverage tacit knowledge and, on the other hand Systematic processes exploit explicit knowledge. Nevertheless, meta-cognitive methods with prescriptive procedures leverage both type of knowledge.

Both cognitive and systematic methods of problem solving have strong and weak points. The importance of individual knowledge is crucial in problem solving activities, and then it's important to combine the power of systematic approaches, in order to overcome with efficient processes the boundaries of personal creativity, with the capability of cognitive methods to leverage individual tacit knowledge.

3.2 Computer-Aided Systems for Problem Solving and Conceptual Design

The domain of Computer Aided Innovation (CAI) includes systems aimed at assisting Inventive Problem Solving by stimulating creativity and guiding towards suitable problem solving paths.

In the last decade, Information Technology systems have substantially fostered a shared vision of creative patterns among different disciplines, resulting in a consistently growing interest in creativity concept [17]. This led towards the birth of a novel and fertile field of research, namely the interplay between creativity stimulation and computer systems. Given the development of software systems that support the human creativity, Lubart [18] eventually proposes a classification among the ways such aid is provided, with a growing degree of machine involvement:

- by facilitating the management of the working process, encouraging the perseverance of designer in the research of innovative solutions;
- by easing the communication between design team members, since circulation and integration of ideas play a relevant role in the creative process;
- by aiding the designer with a coaching activity, acting as an expert system that guides the user throughout cognitive processes;
- by cooperating in the creative process, thanks to the Artificial Intelligence systems that contribute to ideas generation.

Across all kinds of computer supports for the exploitation of creativity, some emerging issues are argued about the development and the requirements of these systems, thus including those mostly addressed to conceptual design and problem solving. Within computer based environments, Hewett [19] remarks that creative key conditions and processes are not domain specific, as well as the need is stressed for analysing different facets of the problem under different perspectives. Shneiderman [20], performing a review of well-acknowledged design principles to support creativity, highlights the importance of outlining the steps that led to partial solutions in order to maintain comparative criteria for evaluating different options.

It is beyond the objective of this manuscript to provide a complete state of the art of principles and hints that are suggested for successful creative CAI tools. However, the issues that have been briefly introduced provide a common background and a sufficient support in order to reveal inadequate features of the software systems that have implemented the four problem solving methodologies described in the Section 3.1, regardless of the predominance of cognitive or systematic aspects. The CAI applications with a brainstorming framework reflect the recalled lacks of the methodology in selecting the most promising solutions due to the lack of assessment criteria; nevertheless in [21] it is claimed that several cognitive methods, including Brainstorming, have been implemented into software tools. Beyond their preferential development as Artificial Intelligent systems for help desks and customer services, CBR tools are characterized by being strongly domain specific. By their definition and way of working, CPS systems relentlessly lead to the embodiment of a trade off among various requirements, since they propose only partial resolution of the problem by constraints relaxing [22]. Regarding TRIZ based CAI tools, classified among the most diffused software systems for idea generation [21, 23], their main limitation stands in the implementation of a “generic scheme (almost algorithmic) for designing new product or concept from existing ones", providing "inventions of only incremental nature" [24]. Thus the richness characterizing the systematic problem solving paths of TRIZ gets lost together with the abstraction capabilities and the range of aspects otherwise depicted. Also other authors [25] judge unsatisfactory the performances of currently available TRIZ software, appointing the attention to a closer link with other design tools and to role played by "dialectical thinking in inventive problem solving and innovation". Figure 5 shows how much the abovementioned methods have been implemented into software tools together with their adaptability to case studies in different fields of technique.

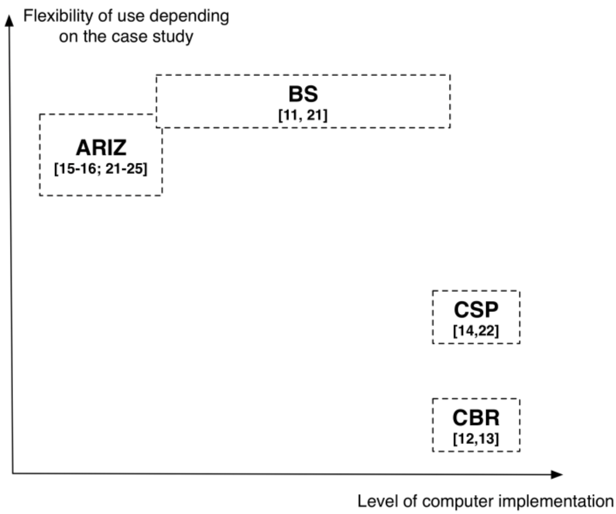

Fig. 5. Flexibility of the four problem solving method briefly presented in the paper, compared to their level of integration in computer-aided tools

3.3 The Role Played by the Information Gathering Task within Conceptual Design

The literature clarifies how information gathering currently requires a meaningful amount of time spent by designers, especially during the conceptual design stage. At the same time engineering designers, especially those with limited experience, are not always aware of the information they require [26]. Interpersonal communication emerges as a key resource for progressing design problems in a practical way: designers generally prefer to source knowledge and information through informal interactions with their colleagues [27].

However, it is expected that designers will increasingly have to rely on retrieving information captured and stored independently of human memory. These reasons provide compelling evidence about the need, for computer-aided problem solving frameworks, to quickly and correctly formulate queries for the investigation of knowledge databases. As a consequence, with the aim of speeding up the search for valuable information, particular attention has to be paid to the analysis of the encountered problem, so that the main criticalities are individuated, as well as the most characterizing technical parameters, features, elements of the system. A CAI tool for supporting conceptual design therefore requires to guide the user in an accurate and systematic examination of the problem to be faced, clarifying the scopes and the priorities in the solution search, especially in the cases characterized by multiple tasks, complex situations, and tangled interrelations among parameters, effects and physical phenomena. The utmost aim should be to provide the designer, downstream the situation analysis, a limited number of solutions, characterized by promising development and great feasibility.

4 The Opportunities Offered by Dialogue-Based Systems

Within the methods supporting conceptual design with an intensive human involvement, which are currently deemed to be more reliable [28], a dialogue-based system represents a chance for embodying an application to support inventive problem solving in a CAI system. The human-computer dialogue field is claimed to be a rather developed technology and questionnaires administered in a digital form are widespread and increasing. The strong points of computer based dynamic questionnaires lie upon their speed in being carried out [29] and suitability within information retrieval systems [30].

The removal of specific jargon to support users without wide vocational experience, regardless the theoretical support to be chosen for a novel CAI application, encourages to develop a dialogue by the employment of natural language. The literature clarifies that natural language processing is widespread and employed in different engineering domains, as reviewed in [31]. The research opportunities emerging within design field by linking natural language to engineering and technical concepts [32], resulted in an increased interest on questioning techniques. Eris [33] has thus introduced new question categories within well-established taxonomies, by observing the nature of commonly asked concepts within design process. The observations he had carried out gave rise to Generative Design Questions, i.e. explorative queries representing the designer's diverging way of thinking, that investigate possible outcomes and embodiments of a system, as well as the ways to achieve the desired outputs.

As a consequence of the developing research field, the attempts of applying Question-Answer techniques within design process are quite diffused. Wang and Zeng [34] have elaborated an iterative question asking method with the aim of correctly identifying the requirements of new products on the basis of customer surveys. Andersson [35] employs a Question-Answer tool to be employed in the final design stages, such as the verification of the product requirements. Less efforts have been paid towards the employment of such tools within conceptual design.

A particular branch of question-answering sequences in the field of conceptual design has been developed to support Conversational Case-Based Reasoning (CCBR), an extension of the Case-Based Reasoning paradigm [36]. The most relevant advantages of CCBR are related to its capability to incrementally elicit the problem formulation through the interactive dialogue with the user [37], as well as their flexibility of use and the ease of implementation [38]. Unfortunately their employment domains rarely overlap with engineering design.

The dialogue based system, that is individuated as a chance for a proper CAI system, should thus strive to fulfil the benefits highlighted in the brief overview of Question/Answer techniques, such as effectiveness, simplicity, ease of implementation, capability of following the divergent thinking process inherent to design.

The authors believe that, through a dialogue-based system undertaking the abstraction process, a systematic succession of questions is viable to support the investigation of the problem, allowing even to highlight the least codified aspects, that otherwise would be hardly taken into consideration. The questioning procedure could advantageously foresee differentiated set of queries focusing on various facets of the problem. The logical succession can thus guide the user towards the identification of criticalities and conflicting issues and subsequently to the search of useful technical and scientific information.

5 Conclusions

The paper has investigated and highlighted the main requirements that a novel CAI system should fulfil in order to support inventive problem solving activities within the conceptual design stage. The findings of the present research can be thus summarized in the following major capabilities that should characterize innovative software applications:

- to face inventive, difficult, non-typical and ill-structured problems;
- to overcome the dichotomy between cognitive and systematic problem solving models, in order to both exploit user’s knowledge and guide the design activity towards the solution with a step by step process;
- to allow a wide description of the problem, that enlarges the potentialities of solutions from different expertise domains;
- to provide comparative means among the feasible solution concepts;
- to link the design process with valuable external sources of information;
- to take advantage of the opportunities given by Question-Answer techniques in terms of such effectiveness, simplicity, ease of implementation;
- to use natural language in order to assist users with poor scientific background about well-established problem solving methods and with the aim of assisting the designer’s thinking process.

As recalled in the Introduction, such features are taken into account in the complementary paper [39], that illustrates an original algorithm proposed by the authors to aid the investigation of an engineering problem.

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Computer-Aided Problem Solving - Part 2: A Dialogue-Based System to Support the Analysis of Inventive Problems

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Abstract. The paper illustrates an original model and a dialogue-based software application that have been developed by integrating the logic of ARIZ with some OTSM-TRIZ models, in order to guide a user, also with no TRIZ background, to the analysis of inventive problems. The dialogue-based procedure brings to the construction of a model of the inventive problem, which is used both to trigger new solutions by highlighting different solving perspectives and to start an automatic knowledge search within technical and scientific information. The prototype system has been tested with students at Politecnico di Milano and at the University of Florence. The paper details the structure of the algorithm and the results of the first validation activity.

Keywords: Computer-Aided Innovation, problem solving, OTSM-TRIZ, conceptual design, dialogue-based system.

1 Introduction

Despite TRIZ is recognized among its expert practitioners as a theory which efficiently improves individuals and organizations problem solving capabilities, its wide dissemination is still dramatically limited by the learning efforts required to master its tools and to assimilate its original thinking logic. Among the main causes which hinder its diffusion in the industrial world, a relevant role is certainly played by the investment needed to introduce TRIZ logic and tools in the existing product development cycle. Several organizational and educational models have been proposed so far, as also in [1], but still several critical open issues remain:

- The percentage of people who starts adopting some TRIZ instruments after attending an introductory course is very limited.
- "Simplified TRIZ", too often intended as a fuzzy application of the contradiction matrix and the inventive principles, is closer to a brainstorming session with guided "stimuli" rather than to the TRIZ problem solving process, and indeed its potential is much more limited. Thus, a conflict exists between a proper assimilation of a TRIZ "way of thinking" and the time available in the industrial reality to learn and practice.

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- Such a conflict is even tougher for SMEs, since in a small organization each employee covers several roles and it is quite impossible to dedicate sufficient time and efforts to TRIZ learning, while keeping the other functions.
- Several TRIZ-based software applications have been proposed in the market since the '90s, but these systems are not useful to speed up the TRIZ learning process and are marginally usable by people without any TRIZ background. Indeed, many companies, that in the past acquired some licenses of these applications without a proper TRIZ education, largely contribute to the promotion of a bad image of TRIZ.

Especially in the last decade, the literature witnesses the need to create TRIZ-based tools addressed to help non-practitioners, with the double purpose of offering intuitive ready-to-use problem solving skills and providing a learning approach to fully take advantage of TRIZ capabilities. In such perspective Dubois et al. [2] propose an algorithmic framework to support the representation of contradictions and standard solutions. In the same context, the authors decided to start a research activity aimed at defining a new role for TRIZ-based computer applications, i.e. CAI problem-solving "coaches" for non-trained users. According to the authors' intention, being guided by a computer application, a designer with no TRIZ background should be able to improve his problem solving capability since the first usage of the software and at the same time to acquire the ARIZ logic through a learn-by-doing process.

The overall motivation of the research is further detailed in [3], where the general requirements of a computerized system for problem solving are identified through a detailed discussion about typical classifications of engineering problems, approaches to problem solving and related computer implementations, the advantages of a dialogue-based human-machine interaction to elicit his knowledge and stimulate his creative skills.

On the basis of the insights arising from this survey, the authors hereby propose an original dialogue-based system, founded on TRIZ logic, and suitable for software implementation.

According to the conclusions drawn in [3], here assumed as a starting point for the development of the computer-implementable algorithm, in order to support inventive problem solving activities within the conceptual design stage, CAI systems should overcome the dichotomy between cognitive and systematic problem solving models, both to exploit user's knowledge and to guide the design activity towards the solution with a step by step process. The system should also allow an abstract description of the problem in order to enlarge the solutions space and to link the design process with relevant external sources of information from different expertise domains. Eventually, the adoption of a natural language dialogue-based interaction with the user can be considered as an effective means to support designers with no specific background on problem solving methodologies, but also to improve their capabilities through a learning-by-doing process.

The paper hence starts with a survey of the conceptual models adopted as a reference to build the computer-implementable problem solving algorithm. Then the structure of the algorithm is detailed, with a careful description of all its modules and an exemplary excerpt from one of them. The second part of the paper describes the experimental activity run with the MS degree and PhD students in mechanical engineering at Politecnico di Milano and University of Florence; the following discussion allows to point out some positive conclusions about the potentialities of the proposed algorithm and also to identify further directions of investigation.

2 Development of a System to Support the Analysis of Inventive Problems

The double goal of fully exploiting TRIZ capabilities and envisaging both cognitive and systematic aspects of problem solving methods, as a need emerged by the review reported in [3], has been the basis for the selection of the theoretical pillars and the models to build a Computer-Aided problem solving framework.

Moreover, the mentioned survey has addressed the authors towards the development of a dialogue-based system for assisting the inventive tasks of the conceptual design phase. This section briefly mentions the theoretical reference items and details the original dialogue-based algorithm developed by the authors as the foundation for the software problem solving application.

2.1 OTSM-TRIZ Models as a Meta-Cognition Framework for Inventive Problem Solving

As discussed in [3], a synthesis beyond the dichotomy between cognitive and systematic approaches to problem solving allows to avoid trial and error, build efficient procedures, leverage the available knowledge resources of individuals and teams and highlight knowledge lacks to be covered with new information sources.

According to the authors' experience, the most comprehensive and organic suite of models describing a problem solving process with the abovementioned characteristics is provided by OTSM-TRIZ [4] and includes:

- Hill model (abstraction-synthesis);
- Tongs model (from current situation to ideality, barriers identification);
- Funnel model (convergent process);
- System Operator (system thinking).

These models should not be considered as alternative paths for transforming a problematic situation into a solution, but as complementary descriptions of the characteristics of an efficient problem solving process.

As recalled in the Introduction, TRIZ has been proved to be a very useful help to designers for developing innovative products. Its set of tools and concepts allows to provide reliable results when addressing non-typical problems. However, substantial limitations arise due to the considerable learning efforts required to master its logic and tools, as for example witnessed by well known industrial players within the TRIZ community [5, 6].

For this reason, a specific goal of the present research is to allow even users without a strong vocational experience to achieve viable conceptual solutions. Moreover, due to the given market boundaries, the recourse to time-consuming and potentially expensive specialization courses has to be excluded. This issue is especially relevant for SMEs, for which a considerable growth in the need to employ systems and software for innovation is expected [7], that therefore could be considered the primary users of the tool under development.

Since the innovation system has to be addressed mainly to inexperienced practitioners, particular attention has to be paid, beyond the foolproof use, towards the removal of TRIZ specific terminology. Thus the application has to foresee TRIZ models, but the user/system interface has to be built through a common language, using at the greatest extent terms and concepts introduced by the designer himself/herself.

2.2 Description of the Algorithm: Logical Blocks and Further Outputs

The original contribution of this paper is constituted by an algorithm for problem analysis, structured in the form of a dynamic dialogue, suitable for implementation in a software application. The underpinning logic of OTSM-TRIZ and several classical TRIZ tools are integrated in order to widely describe the topic of the investigation and to remark the most relevant issues to be considered for the problem solving activity and, if necessary, for the knowledge search.

The dialogue based system helps at first the user in exploiting his know how by suggesting problem solving paths, that don't require external expertise to be implemented. Thanks to the investigation of the parameters affecting the undesired issues arising in the system, the designer can individuate factors to be modified in order to reformulate the problem as a typical case. Moreover, among the outcomes of the innovation system, the algorithm provides indications for suitable problem solving alternatives through different TRIZ tools, e.g. separating in time/space, trimming useless or low-valued components, opportunities to turn the undesired effect into a useful output, re-thinking the ways to perform the main function or to deliver the same benefits.

However, as already summarized in the introduction, the formalization of the problem should also aid the knowledge search, being the information retrieval within the expertise domain preferable to that in external fields, due to an easier and quicker implementation of the generated ideas. In any case, the knowledge search outside the expertise domain should be accomplished just when the abstraction process has been completely and successfully performed, i.e., when a so called physical contradiction has been correctly formulated.

In order to fulfil the requirements and to cover all the options for problem solving and knowledge search, the framework of the algorithm includes a set of logical blocks aimed at examining different aspects of the system to be designed and/or improved. The network of links among the blocks and the single nodes of the algorithm determine an extensive bundle of paths and cycles to refine the problem formulation, depicted in Fig. 1.

With the objective of easing the usability of the system and the formalization of the problem, the following measures have been taken:

- the nodes of the algorithm are either open questions, choices or messages, intended to provide proper hints in performing the problem solving process;
- the questionnaire employs a common terminology, avoiding TRIZ jargon;
- the text of questions and suggestions resorts to previously introduced terms and items;

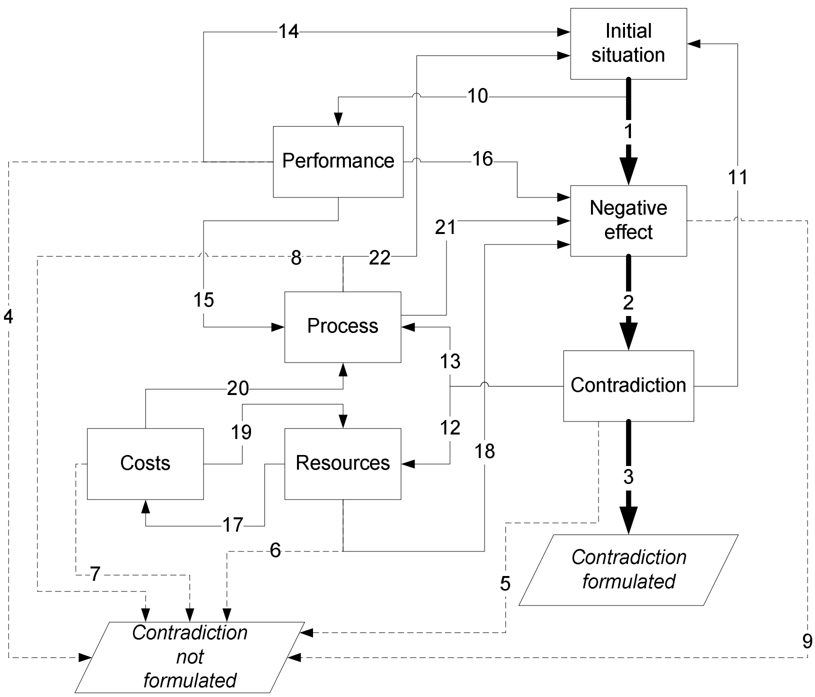

Fig. 1. Network of logical blocks and outputs of the questioning procedure

- some answer examples are provided, as well as their grammatical form, in order to clarify the purpose of the open questions and to provide a more sound text in the downstream nodes of the algorithm;
- the questioning procedure is rich of checks in order to verify the correctness of the user's inputs and to provide a feedback to the user about the outcome of the dialogue.

With the objective of addressing the user towards the most proper description of the situation, the algorithm performs a preliminary distinction among tasks concerning the presence of negative effects or drawbacks, the required implementation of new useful functions and the enhancement of systems with relevant under-performances. The individuation of an undesired effect should lead to the investigation of the features and the phenomena that provoke it and, subsequently, to the formalization of a physical contradiction, grounded on a control parameter leading to mismatching outputs according to the value it assumes. However, even when the user doesn't address the formulation of the problem through the task concerning the elimination of a harmful output, several attempts are carried out with the aim of redefining the model of the system under investigation. The objective is to lead the user towards the formalization of the negative effect responsible for the unsatisfactory or missing functions and, eventually, towards the identification of a contradiction. The most straightforward path for formulating the contradiction, remarked in Figure 1 with thicker lines numbered 1, 2 and 3, involves the accomplishment of three logical blocks, intended to assess the initial situation (labelled as IS), entailing the description of the system through the specification of a wide set of features and correlations with the aim of overcoming psychological inertia, by highlighting also more latent aspects, to define the arising undesired effect (NE) and to identify the conflicting requirements (AR).

However, further ways are foreseen to depict the problem, since several matters can hinder a thorough description of the system under investigation; moreover, lacks of knowledge might occur even within the field of expertise. In case of any circumstance hindering the definition of a contradiction, the algorithm is designed to investigate a wide set of features viable to constitute the core of elements and terms to suggest solution paths or to be sought in proper knowledge bases. The wide description, together with the reformulating attempts, is aided by other logical blocks of the questionnaire, inquiring the designer in order to analyze the circumstances that determine missing functions or cause underperformances (PE), to pinpoint the resources needed by the system to work correctly (RE), to focus on the reasons that imply high costs (CO), to investigate further problems arising during the manufacturing of products or the delivering of services (PR). Eventually, the cases that determine the absence of a contradiction in TRIZ terms, highlighted in Figure 1 with dot lines, include the following:

- the user hasn't seized any possibility to modify the studied system, the phenomena that provoke certain underperformances, the perception of the missed objectives (line 4);
- the attempts to identify a parameter entailing conflicting requirements have failed (line 5);
- the user hasn't succeeded to individuate a proper characterization of the undesired effect in terms of required resources (line 6), high costs (line 7) or problems having reference to any stage of the system lifecycle, whose features are influenced by the design and manufacturing/delivering process (line 8); such characterization is viable, within the questioning procedure, to deepen the description of the system and consequently to reformulate the problem;
- certain individuated criticalities are not considered worth to be further analyzed (line 9).

As explained above, especially in such cases, addressing the problem solving path and knowledge search within the industrial domain of the system to be designed is advised.

Further details about the logical blocks and their connections are provided in the following subsections, within the space limitations of the present paper. Interested readers can get the whole algorithm and even test it, by contacting the authors.

2.2.1 The Logical Block Initial Situation (IS Block)

The questioning procedure starts with this block, whereas a preliminary description of the initial situation is performed. The block is aimed at defining, at first, the technical system to be analyzed, its overall goal (meant as the motivation of its existence, the achievements and the outcomes of its use in terms of the desired modifications of a certain state/condition in the world [8]) and the main function it performs. The beneficiary of the system and the object subjected to the main function of the system are clarified. The designer is then asked to characterize the technical device under investigation following the hierarchical logic of the System Operator and thus delineating the most relevant components, the proper environment to perform the function, the operative conditions. The user, in order to thoroughly describe the initial situation, is required to delimitate the operative space and zone which are involved when the function is delivered. Subsequently the choice of determining the most proper task for the problem under investigation is carried out. If the designer acknowledges missing functions or relevant underperformances, he/she is addressed towards the block Performance (line 10), otherwise he/she is redirected to the block Negative Effect (line 1). In order to to provide an excerpt of the whole dialogue based procedure, Table 1 illustrates the starting part of the algorithm, including the text of the questions submitted to the users. The Table clarifies whether the single nodes require an open text answer (Assignment - ASS) or the choice between two different options (Decision - DEC); the nodes that follow in each case are also indicated. The last column of the Table summarizes the variables that are introduced by the user and that are subsequently reused in the following questions, where they appear in the square brackets.

2.2.2 The Logical Block Negative Effect (NE Block)

The block aims at investigating the undesired effect that arises in the system, as well as the negative consequences and impact. The user is required to indicate, besides the previous items, which element hinder the achievement of the Most Desirable Result by determining the appearance of the negative effect (Tongs model), the operative space and time of such harmful function, alike in ARIZ steps 2.1 and 2.2. A further check is carried out in order to verify whether the element responsible for the undesired effect can be removed from the system without any particular consequence. The accomplishment of the NE block leads the user towards the set of questions that are meant to check the existence of contradiction (AR block, line 2).

2.2.3 The Logical Block Contradiction (AR Block)

The block is supposed to allow the definition of a physical contradiction in TRIZ terms. This step represents the final point of the abstraction process, depicted by the top of the Hill model. The user is requested to focus on the parameters, concerning the previously identified element, that influences the extent of the negative effect. The consequences of modifying the parameters, in the sense of reducing the impact of the negative effect, are evaluated up to revealing the decrease of a desired output. The positive effect which is impaired by a modification of the chosen parameter, as well as its operative time and space, are properly defined along the logical block. The mismatching behaviours faced as a result of increasing/decreasing the chosen control parameter constitute the core formulation of the physical contradiction. The knowledge search holds therefore the purpose, analogously to ARIZ step 3.1, to individuate the opportunities of introducing an X-element, capable of removing the negative effect and providing the jeopardized benefits at the maximum extent, like figured out by the Ideal Final Result.

If any parameter is individuated, whose variation (increase or decrease) provides just benefits without any drawback, the procedure suggests to perform such modification and to reformulate the problem, thus restarting from the initial IS block (line 11). In case of the impossibility to identify a control parameter leading to the physical contradiction, the algorithm guides the user towards a set of suggestion and a meta-block that supports a further characterization of the undesired effect, addressing subsequently the user towards a deeper investigation, carried out in the RE (line 12) or PR (line 13) blocks.

Table 1. Excerpt of nodes and links belonging to the IS block

Step	*Text*	*Type*	*Next →*	*Yes →*	*No →*	*Variables*
1	Type the name of the system that is under investigation. *(Use a substantive, without article, i.e. coffee machine, drill, car...)*	Start	2			[SYS]
2	Does the problem you want to face involve the whole [SYS]?	DEC		4	3	
5	Which technical function is carried out by the [SYS] in order to [GOAL]? *Use the infinitive form of the verb (i.e. keep ink, dry the clothes, deliver a box...)*	ASS	6			[GPF]
12	Type who or what perceives the benefits generated by the [SYS], when it works in order to [GOAL].	ASS	13			[BEN]
13	Describe what or who undergoes the modifications carried out through the action "to [GPF]".	ASS	14			[OBJ]
16	Define the instant or the initial condition in which the [SYS] starts/start to [GPF].	ASS	17			[FOTB]
17	Define the instant or the end condition in which the [SYS] stops/stop to [GPF].	ASS	18			[FOTE]
24	Is your task related to an inadequate/unsatisfactory fulfilment of a desired benefit produced by the [SYS]?	DEC		PE block	NE block	

2.2.4 The Logical Block Performance (PE Block)

The block Performance is addressed to reformulate the system under investigation or the undesired effect. It is accessed whenever the user recognizes any kind of underperformance of the system or the need for introducing a new function. First, it is required to define a performance to be enhanced or satisfied by the implementation of the new function and to explain the motivations for the increase of the performance itself. The user is then asked to individuate who or what would perceive the benefits of the improvements, who or what doesn't allow the enhancements in the current technical system. If any of the previously identified items is viable to be modified, the user is suggested to change the technical system under investigation, working on such object and consequently coming back to IS block (line 14). If the designer individuates that a modification of the production process should be carried out in order to achieve the improvements, the algorithm directs the problem solving procedure towards the PR block (line 15). As a last option the designer is asked to formulate the negative effect of the system in terms of an unsatisfactory performance and consequently to follow the NE block (line 16).

2.2.5 The Logical Block Resources (RE Block)

In several cases, the excessive amount of resources spent by a technical system is considered just as an administrative drawback due to the fulfilment of certain product/service requirement. The block is accessed when the user, failing to formulate the contradiction, assesses that relevant problems arise during the employment of the system. This logical block aims at investigating which resources the system needs for working correctly, classifying them in terms of space, time, information, material and energy. In case the designer judges the direct costs as the most critical resources spent during the system lifecycle, the algorithm guides him/her towards the CO block (line 17) for analyzing the reasons of the high expenditures. Among the amounts of resources spent the user is asked to determine which ones represent the most challenging criticalities and whether this issue can be assumed as the negative effect to be treated by the algorithm. In case of an affirmative answer, the user is redirected towards the NE block (line 18).

2.2.6 The Logical Block Costs (CO Block)

In TRIZ terms, costs are seen as quantities to be prevented having reference to the employment of resources or to inaccuracy of any product development stage. The logical block is aimed at classifying what provokes high costs for the system use, production or maintenance. The resources provoking high costs, as a consequence of their excessive consumption, are clustered with the same criteria of the RE block. The questioning procedure directs the designer towards the RE block (line 19) if the costs concern the user of the system, whilst it guides towards the PR block (line 20) if the expenditures characterize the production process.

2.2.7 The Logical Block Process (PR Block)

This logical block concerns the investigation of further criticalities related to the manufacturing or delivering process. The user is directed towards the block when the formulated undesired effect, which hasn't allowed the identification of a contradiction, arises during the production process or characterizes the whole lifecycle of the system, as well as when unsatisfactory performances, flaws or high costs originate during the manufacturing stage. The scope of PR block is to reformulate the negative effect and the element that provokes it (line 21), downstream the individuation of the critical issues concerning the operations that concern with the production of the system. Since the focus of the investigation could be moved from the product to the design, manufacturing and assembling phases, the questions let the user change even the system to be analyzed (line 22).

2.3 Implementation of the Algorithm in a Web Based Application

In order to allow an extended testing activity, the algorithm has been implemented in a web platform. Thanks to this choice, each tester holds the possibility to extensively proof the dialogue based system and the analyzers can observe the whole set of results remotely.

The so built web application allows to reuse, in the formulation of downstream questions, the terms and concepts introduced by the users, thus providing a clearer explanation of the system's requests along the dialogue between the human and the computer. In the perspective of linking the TRIZ-based problem solving procedure with a knowledge search, as for example proposed in [9], a web application results the most convenient resource to speed up the information retrieval process.

3 Testing Activity and Discussion

The present section, first describes the organization of the testing campaign set up to validate the proposed algorithm. Then, the results of the experimental activity are discussed in terms of efficiency, estimating the effectiveness of the system through a comparison of the outputs with previous experiences and its robustness, by evaluating the repeatability of the outcomes.

3.1 Test Group and Test Cases

The proposed dialogue-based algorithm for problem solving has been tested by 30 Master Degree students in Mechanical Engineering at Università di Firenze (Florence, Italy) and at Politecnico di Milano (Milan, Italy). All these students had firstly received 20 lecture hours about TRIZ fundamentals; then, carried out manual tests have highlighted extremely different proficiency results in terms of their problem solving skills.

Further tests of the elaborated dialogue-based system have been performed by a group of 4 PhD students and a postdoctoral research fellow in Mechanical Engineering with no TRIZ background, in order to appreciate differences and similarities according to different level of competences.

The testing activity has been carried out in computer laboratories where each person, in at most 90 minutes, had to analyze one of three real industrial problems, that were unknown for the participants, in order to obtain unbiased outcomes.

The problems were related to:

- A: Reducing energy waste from an anodizing tank, without creating obstacles to the process;
- B: Extreme wear of the fringe curtain in a X-ray inspection system for food industry;
- C: Complete transfer of oxygen from a large cylinder to several smaller ones, without any compressor.

These problems have been chosen for their different characteristics, in order to evaluate the different capabilities of the algorithm in driving the user towards the logical blocks of the dialogue-based system related with the task (removal of a negative effect, implementation of a new function, enhancement of a given performance), which was considered the most proper for each case study. Although each problem structure depends on the user interpretation [10], it is expected that people model the case A as a typical TRIZ contradiction or as a situation where a given performance is required. The case B clearly points to a negative effect, but should be preferentially modelled as a contradiction, while the case C should address the problem solver towards the implementation of a new performance or the improvement of an existing one.

Finally, the three cases have been divided as follows:

- Case A: 11 students and 2 PhD students;
- Case B: 13 students and 1 PhD student;
- Case C: 6 students, 1 PhD Student and 1 postdoctoral research fellow.

3.2 Overview of the Results and Discussion

The results of the problem situation analysis have been preliminarily evaluated by experts without any formal criterion, according to the following metrics:

- a good result is characterized by a precise description of the problem, without mistakes or misinterpretations, as well as by an appropriate set of features and elements required by the dialogue based system, viable to lead towards an appropriate information retrieval;
- a satisfactory result is characterized by a global comprehension of the problem under investigation, with an almost complete description of its main characteristics; the available information about the problem can support a preliminary direction of research for information gathering;
- an unsatisfactory result relates to a poor description of the problem, rich of misinterpretations and with no useful information capable to enlarge the potential solution space.

Table 2 provides an overall outlook of the results gathered by the Master Degree Students from both the Universities; PhD students were considered separately. In the assigned time, more than the 60% of the Master Degree Students were driven towards one of the final nodes of the algorithm, as well as 23 out of 30 (76,6 %) gave at least a satisfactory description of the problem situation. However, just a small part of them (13,3% of the grand total) formulated a complete model of contradiction. A comparison between the Master Degree students from both the academic institution, does not highlight particular differences, since they obtained positive results for about the 75% of the analysis (approximately 80% in Florence and 70% in Milan). However, it is important to mention that students from Politecnico di Milano totally got better quality results (good, roughly 54%; satisfactory, 18%) than their mates from University of Florence (good, about 37%; satisfactory 42%).

Table 2. Overview of the results: quality of the problem description and percentage of formulated contradictions

	Florence students	***Milan students***	***Students from both Institutes***
Completed procedure	63,2%	63,6%	63,3%
Formulated contradiction	10,5%	18,2%	13,3%
Good result	36,8%	54,5%	43,3%
Satisfactory result	42,1%	18,2%	33,3%
Unsatisfactory result	21,1%	27,3%	23,3%

The students who properly formulated a contradiction through the dialogue-based system achieved the best results in terms of abstraction according to the Hill Model: they got to the description of a physical contradiction and also identified the main characteristics that the solution should have in order to positively overcome the problem. Consistently with the problem solving models proposed in section 4.1 the algorithm has proved to be successful in stimulating the user in refining the problem under investigation, by asking him/her whether the detail level of the analysis is correct, allowing consequently to focus on different hierarchical levels of the system, thus moving upwards or downwards in the System Operator (more than 50% of the students have modified their initial definition of “system”).

The convergent process described by the Funnel Model emerges by analyzing the body of results produced within this testing activity: the students, by following similar paths of investigation, frequently converged towards the same problem model, answering the questionnaire with similar definitions for the needed variables, even if, in many cases, this hasn’t resulted sufficient for formulating an appropriate contradiction.

By thoroughly investigating the procedures carried out by the students that obtained good results, it’s important to highlight that many of them achieved great benefits by changing the definition of the “technical system”: they progressively changed the scope of the problem by identifying the right detail level and the critical features to be improved or to be removed. It is noticeable that all these students, regardless of the test case under analysis, considered the problem related to unsatisfactory or even missing performances of the technical system. The iteration of the procedure gave them a different perspective of the whole problem and by means of problem reformulation one third of them identified a critical contradiction for the problem solution. The students of this group that didn’t get to the definition of a contradiction anyway leveraged their knowledge in order to give a description that made sense and however viable for a profitable information retrieval. The greatest part of these students (about 85%) came indeed to one of the final nodes of the procedure with positive conclusions.

On the other hand, the students that didn’t succeed in obtaining valuable results often followed an odd logic since they experienced some difficulties in distinguishing between elements/components of the system and their related parameters. About half of them tried to force the procedure towards the direction of a solution they had intuitively elaborated, rather than using the dialogue based system as a guiding tool to gradually explore the characteristics of the problem under investigation. Differently from their colleagues that obtained positive result, the greatest part (around 57%) of these students didn’t get to the end of the procedure, without taking therefore advantages from the refinement of the definition of the system.

It’s equally important to verify whether the goal of approaching the problem with the right branch of the procedure has been met or not. By considering the sequence of steps that all the students went through, a simple analysis of Pearson’s correlation [11] has been carried out, remarking that the students, regardless their success in exploiting the procedure, followed very similar paths of analysis. Indeed, the lower value of correlation between couples of exercises is approximately 0,72; such evidence can be considered from two different points of view. First, the individual cognitive processes are sensitive to similar education programs; second, the procedure doesn't have the expected capability of driving the user in the distinction of different issues. In order to remove this ambiguity, it is worth to carry out further tests with different people from various expertise fields and with different vocational experiences.

Table 3. Network of logical blocks and outputs of the questioning procedure

	Anodizing tank	**X rays**	**Cylinders**
Completed procedure	72,7%	66,7%	53,8%
Formulated contradiction	9,1%	16,7%	15,4%
Good result	54,5%	33,3%	38,5%
Satisfactory result	45,5%	0,0%	38,5%
Unsatisfactory result	0,0%	66,7%	23,1%

Along the analysis of the results, it is also worth noting that the algorithm still presents some weak points, since the success of the test seems to depend upon the case study. In detail the three case studies led to significantly different overall results, as depicted in Table 3.

The "Anodizing Tank" test case (A) produced the best results since no student produced any unsatisfactory description of the problem; on the contrary the case study about "X-rays detection system" (B) obtained very contradictory results: all the positive description are good, however the largest part (almost 70%) are definitely unsatisfactory. The tests about "Cylinders" provided, as well, intermediate outcomes. The heterogeneous distribution of satisfactory results encourages to carry out further tests in order to better understand the adjustments that the algorithm requires.

Another lack emerged by analyzing the results, concerns the marginal capability of the procedure to point out features related to different time periods and situations, as in the logic of System Operator. Just 1 tester out of 30 has individuated problems and resources pertaining circumstances that are displayed both before and after the operational time of the main function of the investigated system. The majority of the students, more precisely 23 out of 30, have identified resources useful for problem solving either before or after the reference operational time. On the other hand, 6 students have taken into account in their analysis just characteristics that are relevant within the time interval of the carried out primary function. The development of the algorithm has to take therefore into account strategies to investigate the resources and the characteristics of the technical system and its surroundings along the whole lifecycle of the analyzed object. The advantages of such more detailed survey have to be consequently examined in terms of improved capabilities to describe the problem situation and formalize contradictions.

For what concerns the potential differences in the solving path followed by more specialized people, the group formed by the PhD students and the postdoctoral research fellow produced only good or satisfactory results. In three cases they got to a good formulation of a contradiction, thus abstracting the problem and identifying the main features of the solution. In the remaining two cases the description of the problem is just satisfactory, but useful to perform a preliminary information search through the available sources (patents, scientific and technical literature), through which it is possible to enhance and refine the analysis itself or to find proper solutions.

3.3 Comparing Computer-Aided and Individual Problem Solving Skills

As clarified in Section 3.2 the same test group of MS students had been previously involved in manual tests without any computer support. The proof was carried out with the possibility to access their own books and the slides of the 20 hours course they had attended. Nevertheless, the amount of lecturing hours about TRIZ they were subjected is not deemed to particularly enhance individual problem solving skills.

By comparing the overall outcomes of the manual tests with traditional tools, giving indications about students' problem solving skills, and those obtained through the proposed dialogue based system, the share of students showing negative results drops from roughly 35% to about 27%.

However, an in-depth analysis of the results highlights that students that had shown good problem solving skills (approximately 46% of the grand total) didn't obtain particular benefits in approaching the situation by means of the dialogue-based system (Table 4). One third of them described the problem by modelling it correctly, while the remaining two thirds produced a worse analysis than the one they could arrange without guided support (although with different case studies). It is worth to mention that just 15% of them produced a complete unsatisfactory model of the problem, while the others depicted it at least at a satisfactory level. On the contrary, the greatest benefits of the procedure (Table 4) emerge with those students that had previously showed more limited (just satisfactory or even poor) skills in the employment of systematic problem solving methods and tools (respectively 19% and 35% of the grand total). In fact, 80% of the first ones and 56% of the second ones described the problem in a more appropriate way than they had been capable without exploiting any support. The carried out analysis helped them in both correctly identifying spaces of solution that hadn't previously emerged because of psychological inertia or lack of knowledge and narrowing down the direction of research for useful information aimed at problem solving purposes.

Table 4. Positive and negative outcomes of the proposed system compared with the different Problem Solving skills of the students that carried out the testing activities

	Whole test group [%]	*Positive outcomes with the proposed system [%]*	*Negative outcomes with the proposed system [%]*
Students showing good problem solving skills	46,2%	83,3%	16,7%
Students showing satisfactory problem solving skills	19,2%	80,0%	20,0%
Students showing poor problem solving skills	34,6%	55,6%	44,4%

3.4 Proposals for the Enhancement of the Dialogue-Based System

The limited capabilities shown by the algorithm in terms of exploring the topic of the investigation along the system lifecycle represents a primary issue for the improvement of the procedure. The capability to map the features related to the past and the future of the system represents a further opportunity for monitoring the mutual relations among the parameters and the elements that are relevant in the display of the undesired effects. With this perspective the authors are working on the introduction of a novel logical block, System Operator (labelled as SO), regarding the investigation of the thorough timeline during which suitable actions are viable to eliminate or attenuate the main undesired effects of the system. On the basis of the authors' vision, the user can be guided throughout such deeper investigation, whenever, with reference to the current version of the algorithm (lines 4-9), no successful formulation of a contradiction is emerging. The outputs of the block can be a hint to move the focus of the analysis towards a different system (thus linking to IS) or the individuation of control parameters relevant within a conflicting issue (thus addressing to AR). The last two options are represented in Fig. 2 by the lines 23 and 24, respectively, while a novel flop in defining the contradiction is remarked by the line 25.

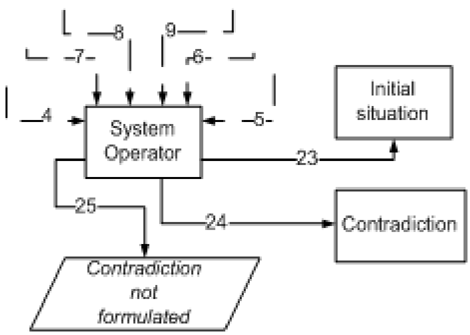

Fig. 2. Partial network of logical blocks regarding the modification of the current procedure

A further planned measure to be attained regards the introduction of graphical elements to depict, after each answer by the user, the current schematic representation of the problem described so far. According to the authors' thought the pictorial display of the topic schematization is viable to facilitate the learning process of the logic and to highlight further mistakes and/or misinterpretations concerning the introduced variables

4 Conclusions and Future Activities

The present paper proposes a model for computer-aided systematic problem solving, which has been adopted as a reference for the development of an original algorithm aimed at guiding designers, even without any TRIZ background, in the generation of inventive conceptual solutions. The tool has been built aiming at fulfilling the requirements that should characterize CAI problem solving systems, emerged in [3], and regarding the problem investigation tasks. Such requirements refer to the capability to face the distinctive aspects of design problems and to perform a detailed description of the initial situation, beyond the advantages originated by the employment of natural language within dialogue-based systems.

The algorithm has been implemented in a prototype web application already tested with MS and PhD students both from Politecnico di Milano and University of Florence, obtaining positive results especially with the students with poorer systematic problem solving skills.

The tests performed so far have demonstrated that the proposed system is suitable to combine several expected benefits of the most acknowledged problem solving techniques. First, cognitive capabilities are enhanced by soliciting the analysis of the problem from different perspectives, thus overcoming psychological inertia as typically addressed by brainstorming sessions and the TRIZ System Operator. Compared with brainstorming, the analysis follows a more systematic path, avoiding useless trial & errors, with consequent benefits in terms of process efficiency. The personal knowledge of the user is leveraged to solve the analyzed problem by suggesting suitable TRIZ separation principles, once that a proper model of contradiction limiting the applicability of typical solutions has been built. Indeed, while the overall results of the test have been satisfactory, the proposed algorithm needs to be definitely improved in the support to the identification of a proper model of contradiction, mostly in terms of recognizing the critical design parameter characterized by conflicting requirements in order to satisfy different evaluation parameters.

The system is also structured in order to elicit lacks of knowledge by the user, either in terms of limited understanding of the mechanism originating the problem, or missing physical/chemical effects suitable to deliver a certain function. Such knowledge lacks will be used as inputs for a patent-mining tool capable to extract relevant information from patent texts within or even outside the problem domain. The complete system will be tested within a project of the EraSME EU Programme, by involving Small and Medium Enterprises from Italy and Spain.

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A Computer Aided Strategy for More Sustainable Products

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Abstract. This article presents a methodological study on the potential use of structural optimization strategies for eco-design to support engineers during the design process of green products. The structure of the traditional process of eco-design now depends on the personal skills of the designer and his ability to integrate in the traditional design process the requirements of eco-sustainability. The objective of this study was to address guidance on integrating environmental aspects into a computer aided inventing product design and development extending the functionality of the traditional design process to green product design. The proposal arises combining eco-inventive principles with the design approach based on structural optimization tools so creating a knowledge–rich CAE process linking CAD, FEM, Optimization tools and LCA based tool. CAI tool is used to generate unconventional geometries and to trace the best promising direction of intervention. LCA integration allows the user in real-time to measure the environmental impact of his design choice calculated as a variation on the main indexes of environmental sustainability. A case study about the eco improvement of a steering plate for trial motorcycles is presented and discussed with the aim to introduce potential benefits of such an inventive eco design approach.

Keywords: Eco-design, Inventive Design, Structural Optimization, CAI, Eco guidelines, TRIZ.

1 Introduction

In former times, engineers were only concerned about designing a product that met its objectives. Little attention was given to the future availability of natural resources. Current design trend is changing. The product not only has to fulfil its objectives/functional performances, but it also has to fulfil market needs and ensure minimal material and/or energy wastage. To make innovation means to begin a process in order to create value modifying a set of the system variables [19]. To achieve this goal, many tools have been conceived in order to identify where it is more useful to intervene, and how to improve current products and processes. To order them, Knight [1] grouped these tools in 3 categories:

1. Guidelines defined as providing broad support, with little detail, but applicable either across the whole product development process and lifecycle, covering a

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significant area (e.g. design for recycling; design for disassembly; design for lifetime optimization. See for example [1–4]).

2. Checklists defined as providing in-depth, but narrow, application at selected stages of the product development process or lifecycle (see for example [5–7]).
3. Analytical tools defined as providing detailed and/or systematic analysis at specific stages of either the product development process or lifecycle, e.g. eco-indicators; environmental effect analysis; environmental impact assessment; life cycle assessment; material, energy and toxicity ('MET') matrix; life cycle cost analysis (see for example [8–13]).

Most of them can be considered as excellent tools, they are easy to use, well organized, and time-efficient. However, they do not provide a mechanism to prioritize the environmental requirements and deploy them into the product development process [14]. The most structured and widespread tool for assessment is certainly Life Cycle Assessment (LCA); it is used to measure, evaluate and report the resource requirements (raw materials and energy) and environmental emissions related to a specific system. LCA has a key strength in its quantitative approach, but this technique requires a huge investment in time and effort, and it is ''not useful in the design process. Companies cannot delay their design process to wait for the results.'' [15]. Unfortunately, LCA approach is too complex and not user friendly [16], and actually doesn't provide any suggestions about how to change design of current product.

Russo et al. [17], positioned a large selection of these tools and methods according to different criterions of classification, i.e. eco-assessment toward eco-innovation.

The capability of performing both assessment and improvement using a unique method could significantly increase the effectiveness of the design process and the robustness of results achieved, but at the moment there is not a winning paradigm to do that.

However, a complete CAI tool should provide suitable ideas according to an assessment phase comprising both performance and environmental requirements. This work put the methodological basis for a CAI concept integrating environmental requirements into product design and development. It combines environmental guidelines, with abridged LCA Software and virtual modeling based on CAD and Structural optimization SW.

An overview of simplified LCA and current tools for environmental requirements assessment/improuvement integration is proposed in order to limit time and costs of the traditional LCA[18]. A different approach is proposed by Darmstadt University [25], they decided to work in a CAD environment more congenial for the designer and generate results by the assessment phase directly in such environment. The promising developments offered by this approach will be analyzed and criticized in section 2.

The overall framework of this work will be presented in the following sections together with an exemplary case study.

2 The Integration of Computer Aided Design for the Sustainable Design

Eco-design [21-22], or green-design, consists in a set of coordinated activities intended to develop products and processes with less environmental impact. The application of eco-design involves a particular framework for considering environmental issues, the application of relevant analysis and synthesis methods, and a challenge to traditional procedures for design and manufacturing. The designer is involved not only in the production and use phase, but also in the entire product life cycle with pre-manufacturing (raw material and processing), end of life and transports.

Four levels of eco-design can be defined as follows:

– Level 1- product improvement: this is a progressive and incremental improvement of the product, a re-styling of the product; for example, it can consist of decreasing the use of materials or replacing one type of fastener by another;
– Level 2- product redesign: a new product is redesigned on the basis of an existing product;
– Level 3- new product concept definition: this is an innovation rupture as technical functions to fulfill product functionality are different.
– Level 4- new production system definition: this occurs when innovation in the productive system is necessary.

In this work a proposal for an innovative framework, especially conceived for levels 1 and 2 of eco-design, is presented.

The suggested methodology is focused on redesigning sustainable products (solids and not fluids), owning at the first and second level of the previous classification. The reason of this limitation is due to the framework adopted to manage such a design process: CAD structure.

The most important tools in the traditional design process are CAD and CAE software. However, current CAD tools help engineers to design a product that meets the functional and structural constraints but they are not able to manage environmental constraints. Only few applications of CAD for eco-design have been identified in literature, and in most cases they are promoted by academic research groups except for Solidworks 2010 that provides a specific module for sustainability.

Although the introduction of eco-requirements in CAD environment is so poor, the structure of the information offers many advantages:

- Product (assembly) is already organized by separated parts allowing an arrangement of results by components.
- Information about material, transport and manufacture process, cost, etc. can be easily associated to each part, so involving other life cycle phases traditionally excluded in a standard design approach.
- Intuitively usable.
- Automatic calculation of masses and volumes by subordinate components or material density.

- Material and item statistics can be easily implemented.
- Easy back tracing of ecological hotspots through the product structure.

The aim of the CAD base tool for Eco-design [23] is to measure variations on environmental impact indexes not at the end but during all the design activity, and so monitoring on time any change onto the product and at the same time allowing to trace the best promising direction of intervention.

EcologiCAD [25], developed in 2004, is probably the first attempt to undertake ecological Life Cycle Assessments during product development. The used structures are similar to the product structures in 3D-CAD systems and doesn't offer guidelines and not even list of materials.

Another interesting attempt is represented by ECOCAD [26], a tool that interfaces to a large number of other instruments, including:

(1) CAD platform with environmental information Product Data Management (PDM), Product Life-Cycle Management (PLM) and Data Base (DB), containing information for the design of mechanical components such as materials, production processes, volumes, geometries.
(2) Platform CAD, FEM and CAM used to create and manage geometric /mathematical information of the components.
(3) LCA and green Guidelines from eco-design pilot [27].

The advantages of this approach is that geometrical information and process are automatically extracted from CAD as volume, surface, and features (holes, bending sheet metal, welding). User has to set materials, connection systems between parts, and processes that are not directly managed by the CAD.

Although the approach framework is very promising, the analysis results are not very reliable, mainly due to two reasons:

- the difficulty of obtaining accurate, completed and updated information DB;
- the lack of an effective integration of design suggestions often representing *common sense ("we do it anyway"), but lack specificity. So where they are already inherent in the design process they need recognition and development* [16].

Finally, for completeness, an example of integration between structural optimization tools and design for disassembly [28] proposed by Willems is mentioned.

In this work CAD and structural optimization tools are currently used to offer to the user important suggestions to redesign the product.

3 Research Approach

A complete work of integration between the eco-improvement suggestions and an aLCA software has been developed by Russo et al. [21] during the European project "Recycling and Resource Efficiency driving innovation in European Manufacturing SMEs" (REMAKE project [29]) in 2010.

The aim of this method was to suggest a new way to perform the assessment phase, based on the identification of the hotspots on which to intervene. Such hotspots are identified by specific ideality indicators and information about resources already employed by the company.

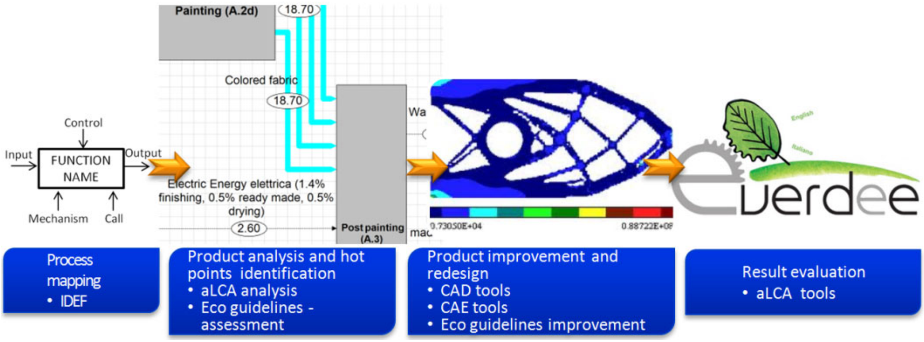


Fig. 1. Tools combination for the proposed ECO-desing approach

The overall process, schematized in figure 2, consists in mapping the process by a modified IDEF0 diagram. Then a software interface translates IDEF data for a simplified LCA software developed by ENEA, called EverdEE software. Once environmental impacts are calculated, a list of hotspots are generated in order to define a list of directions to intervene. Such a list is conceived according to the most promising intervention that can be provided for more sustainable process/product instead of generating the list of items associated with the maximum impact. Improuving phases are supported by a set of Eco-guidelines, presented in the following section. Results are finally compared by eVerdEE tool to provide a quantitative estimate of ECO- impacts. Once the overall process will be fully integrate in a single modeling tool (CAD+ Eco-guidelines+aLCA+ structural optimization sw), it will be possible to suggest users in real time if any geometric modification is going in the right eco-directions and automatically provide a better geometry.

4 REMAKE ECO-Guidelines

REMAKE guidelines being extracted from the TRIZ laws of evolution [30], aiming to reduce resource consumption (mainly material and energy) increasing efficiency. This is possible by taking into account the best heuristics and theories of problem solving, and also taking into account new trends, technologies and best practices in green design.

REMAKE-guidelines allow guiding the designer in order to improve the environmental performance of the virtual product. They actually constitute over 330 actions at user level, organized by pre-manufacturing, manufacturing, product use and end of life.

Each phase contains a set of objects to which the guidelines refer to. For every object a list of goals to be achieved, opportunely translated in terms of resource abatement, is provided in order to design a better product.

A selection of such guidelines has been selected to be integrated as supporting knowledge for an ECO-Design activity based on CAD modeling; in fact they involve the entire life-cycle.

Such suggestions have been adapted to design in order to maximize structural optimizers potentialities, guiding the user to design a less impact product (e.g. working on chemical composition of raw materials, making manufacturing process easier, a lighter and more compact product during the functioning, energetically more effective, easier to transport, disassembly, dispose, etc.).

In this work, the authors show the guidelines related to the material minimization and volume wastage, saving performances and avoiding the complexity of manufacturing.

At differences of other ECO-improvement tools, the peculiarity of this approach is that the designer, following the suggestions directly proposed inside the CAD environment, can visualize in real-time not only how the current phase changes but also the impacts on all the other phases belonging to the whole product life-cycle, thus allowing 360 degree changes.

The results are obtained using the eVerdEE, an aLCA software developed by Enea. This software allows to assess the impacts on a large number of eco-sustainability indicators. It contains well updated libraries and it can be easy interface to information flow moving from a CAD based process.

REMAKE guidelines are organized in 3 levels:

- guidelines with the aim to minimize the target resource;
- guidelines guiding the user on which CAE tool has to be chosen and eventually the proper information library;
- guidelines suggesting the specific strategy to better achieve the desired results.

For some strategies a more detailed path has been developed. Just to clarify, few examples, one for phase, are shown in the following:

In table 1 an example about pre-manufacturing phase, and for use phase is given. The goal is to reduce the impacts, working on product supply phase from cradle to gate, re-setting the geometry of the given piece and of its packaging in order to minimize mass, volume and impact on transports and inner logistics of the materials entering in the factory.

Table 1. One example taken from a list of strategies for the Pre-manufacturing phase, and for the Use phase

Goal	Tools	CAE strategy
Minimize Volume and/or Mass wastage of raw material	CAD modeling + OPTIMIZATION path	Defining the minimum working volume, based on the maximum dimensions of raw material from which the component has to be extracted - set the optimization strategy (topological or free size) constraint and the specific constraints of minimum member size (eventually combine with draw direction and symmetry).

For the sake of brevity we omit the MSTP strategies (Modal Shift Transportation Planner)[20] for optimizing the transports of goods and the PPP tools (Production Process Planning) to better manage the flow and the replenishment of material and machining wastes.

Table 2. One example taken from a list of strategies for the Phase of Manufacturing

Goal	Tools	CAE strategy
Manufacturing Energy and Mass reduction	CAM	Simulation and maximization of the energy-saving of the tool path during CNC machining
	Thermo mechanics coupling optimization	Thermo–mechanical coupling calculation is used for improving optimization performance in order to maximize the Energy-saving and material use during foundry process
	multidisciplinary OPT	Set up the geometry of finished work-piece using a structural optimizer and a proper material

This strategy is based on the assumption that a more compact rough machining impacts in a positive way on all the following phases. So, in this process phase the designer task is to identify the proper shape of the component in order to achieve the desired performance using the minimum material.

The REMAKE guidelines support step-by-step the designer during the creation of different shapes, such shapes are put inside CAD, where they can be evaluated by eVerdEE. In particular, for each shape eVerdEE calculates the global impact on the entire life-cycle.

The result is a series of scenarios comparing the different design choices. In this specific case, the designer will be able to understand if it is better to:

- maximize the raw piece volume as much as possible and working on the minimization of the finished work-piece mass in order to improve the use phase, or potentially the manufacturing phase.
- minimize the raw piece volume as much as possible in order to have greater benefits during pre-manufacturing phase.

In this work the authors focus their attention on the potentialities of topological optimization tools, even though the current guidelines (approximately 20) concern also other different virtualization tools to support the eco-sustainable design activity in all phases, such as:

- CAM, used for instance to simulate and maximize the energy-saving of the tool path during CNC machining.
- Thermal optimization to improve the impacts on foundry processes.
- Multidisciplinary optimization to combine optimization strategies and innovative material choice.
- Computer aided assembly and disassembly for manufacturing and end of use phases.
- Production process planning.
- Modal shift transportation planner.
- Vehicle routing planner to better manage the logistic of material handling, storage, etc.

The following picture shows the integrated ECO-design process. A deeper analysis on how REMAKE Guidelines can be integrated in it is given in the work of Russo [21].

5 Design Optimization

Designing by optimization techniques means translating a design task into a mathematical problem with the following basic entities:

- An objective function, i.e. the performance of the system that the designer wants to reach or to improve.
- A set of design variables, i.e. the parameters of the system affecting the objective function.
- A set of loading conditions and constraints representing the requirements the system has to satisfy.

The optimization algorithm finds the value of the design variables which minimizes, maximizes, or, in general, "improves" the objective function while satisfying the constraints.

The use of computers for design optimization is rather common in several fields since 1980's; besides, during the last years new optimization tools have been developed to solve specific design problems [4]. In the followings the main features of these techniques will be summarized. All techniques can be set up with the aim of reducing mass as least as possible.

In a *shape optimization* process the outer boundary of the structure is modified according to the optimization task. The shape of the structure, modeled through the finite element method, is modified by the node locations: the optimization algorithm, according to the loads and boundary conditions applied to the FE model, changes the coordinates of the nodes which are defined as design variables. The result of the optimization cycle is a deformed geometry of the starting shape structure.

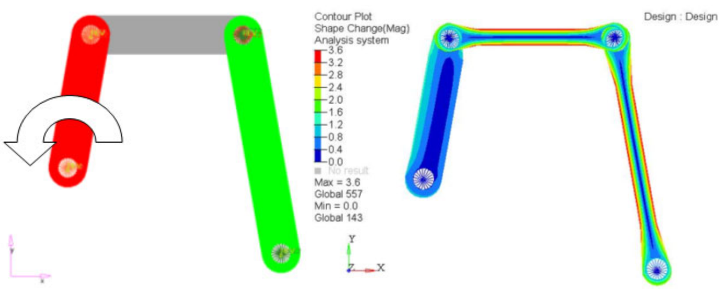


Fig. 2. An example taken from Optistruct tutorials 2009, regarding a mass reduction for a bar linkage obtained by a shape optimization

The *size optimization*, is a special type of parametrical optimization in which the design variables are represented by some properties of structural elements such as shell thickness, beam cross-sectional properties, spring stiffness, mass, etc. During the optimization process these parameters are modified by the algorithm until the expected goal is reached.

Topology optimization is a technique that determines the optimal material distribution within a given design space, by modifying the apparent material density considered as a design variable. The design domain is subdivided into finite elements and the optimization algorithm alters the material distribution within the design space at each iteration, according to the objective and constraints defined by the user. The external surfaces, defined as “functional” by the user, are kept out from the optimization process and considered as “frozen” areas by the algorithm.

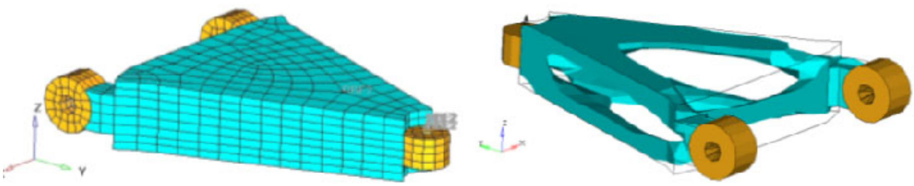


Fig. 3. An example taken from Optistruct tutorials 2009, regarding a mass reduction for a control arm obtained by a topological optimization

Topography optimization is an advanced form of shape optimization in which a distribution of ribs and pattern reinforcements are generated on a specific design region. The approach in topography optimization is similar to the approach used in topology optimization, but shape variables (node coordinates) are used instead of density variables. The large number of shape variables allows the user to create any reinforcement pattern within the design domain.

Moreover manufacturing constraints may be set in order to take into account the requirements related to the manufacturing process. Sliding planes and preferred draw directions may be imposed for molded, tooled and stamped parts as well as minimum or maximum size of the structural elements (i.e. ribs, wall thicknesses, etc.).

From an eco-design point of view, such constraints play a strategic role to obtain the final geometry, that achieves the objectives of mass and volume minimization without increasing the complexity in the manufacturing processes.

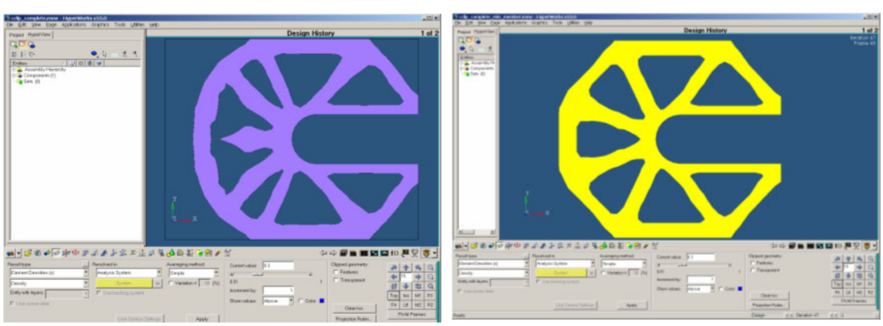


Fig. 4. Comparing between two optimizations. On the right the same piece with minimum member size constraints. Notice the smaller members in the original iso surface plot are replaced by a more discrete rib pattern. The second design is so easier to manufacture.

So, most of optimizers functionalities are already well integrated with an Eco-design view, nevertheless it is necessary to use a network of guidelines in order to better control all the design choices and consider these choices influence the other phases of the product life-cycle. As we said before, the network of guidelines shows some preferred path for combining optimizations between strategies and constraints, and at the same time it gives information about how a choice influence the environmental indicators directly in the design phase and not in the next phases as using validation tools.

6 Case Study

The following case study shows how the guidelines and structural optimization tools can be combined in order to obtain more sustainable products.

In particular, the application of the methodology concerns a steering plate mounted by the Spanish Producer Gas Gas on a wide range of trial motorcycles. The mechanical properties are the same as the ones mounted on the other motorcycles types, but one fundamental requirement of the trial motorcycles plate is the lightweight.

The plate is produced by die-casting process and the production rate is 10.000 units per year. Therefore, this value has been used as a functional unit for preliminary calculation by eVerdEE.

The used guidelines are the same explained in section 4: *mass minimization during the use phase and minimization of raw material volume during the pre-manufacturing phase*. For simplicity, others guidelines related to the manufacturing phase are not take into account in this application.

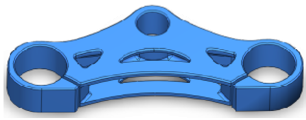
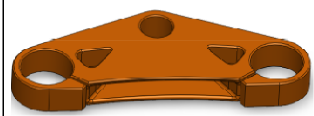
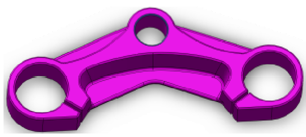
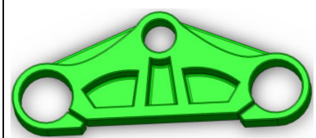
The guidelines regarding to the use phase (topological optimization combined with the constraint of minimum member size, with or without the draw direction constraint) generate 2 different geometric scenarios.

In case of guidelines related to the pre-manufacturing phase, the suggested procedure starts with a modification of the initial volume of the raw piece (in this specific case the volume reduction was fixed arbitrarily at -15%), then the next step is a topological optimization choice (or free size optimization) combined with the same constraints explained for the use phase. So, from the previous step, 4 different geometries are obtained as shown in table 4.

The 4 geometries have been evaluated according to sustainability requirements, considering 2 typologies of production: die-casting process and CNC machining tools. Data, such as working energies, time and material wastes, have been obtained by simulations performed by experts. While, the impacts on transports, packaging and end of life have not been considered, because they are approximated as invariant and irrelevant for the geometries valuated.

Finally, 8 different scenarios were produced (the 4 models realized by die-casting process and the same 4 models calculated using CNC machining tools). Calculation was produced by adopting eVerdEE software. In figure 7, graphs related to environmental impact analysis of the 8 models are shown. The graphs show, for each model, the reduction in percentage of CO_2eq production and the mass reduction in percentage.

Table 3. Alternative plate configurations

	USE PHASE GUID. →Reduce the mass of finite product	PRE-MANUF. GUID. → Reduce the volume of raw material
 Initial product	 Topological optimization: Minimum member size	 Topological optimization: Minimum member size
	 Topological optimization: Minimum member size Draw direction	 Topological optimization: Minimum member size Draw direction

The first comparison emerging from the graph is that, for the batch of production considered, the CO2eq generated by machining is higher than the one generate by die-casting. This difference decreases as the batch decreases.

In case of machining, the best result, in terms of CO2eq, is obtained by the 4th configuration (coming from pre-manufacturing guidelines and adopting the draw direction constraint). This model, compared with the original one, allows a 15% of reduction of CO2eq (equal to 3 Kg of CO2eq). Such a reduction is due to 2 main reasons:

1. The application of pre-manufacturing guidelines, concerning the mass and raw piece reduction. These 2 directions of intervention have an high positive impact on the CNC machining tools.
2. The simultaneous imposition of constrains (minimum member size and draw direction). They influence the manufacturing stage through an high simplification of the finished piece geometry (allowing at the same time a mass reduction).

For machining calculation, the gain obtained, in pre-manufacturing and manufacturing phase, by the 4th configuration is so high that it is convenient even though this variant is heavier than the others. In this case a design strategy aiming at minimizing energy and mass in the phase of use would not have been the right direction.

Also the 3rd configuration gives an high CO2eq reduction, obtained by the volume reduction of the raw piece, but some of the benefits obtained during the pre-manufacturing are lost during the manufacturing. In fact the draw direction constrain has not been set up and so the plate geometry is more complex, this optimization negatively influences the manufacturing.

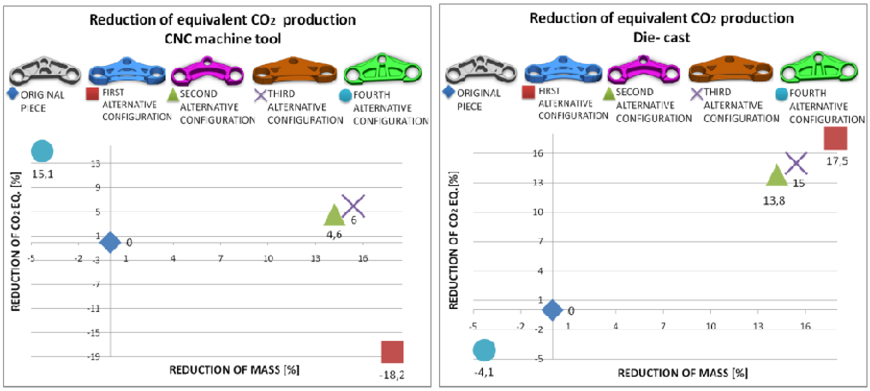


Fig. 5. Graph shows final results of the ecodesign process. Resulting LCA scenarios are calculated in terms of CO_2eq reduction.

In this respect, we can compare the 4th and the 1st configuration. Using the 1st configuration a mass reduction of about 20% can be achieved , but the high resources consumption in the manufacturing eliminates all the benefits gained during the use.

Considering the models related to the die-casting, the best result is obtained by the 1st configuration, that allows a reduction of CO2eq of 17%. This benefit mainly derived from the application of the guideline related to the use, that focus on a mass reduction.

This guideline, for the die-casting process, has an high positive impact also on the manufacturing, because it permits a less resources exploitation (in opposition to the machining case).

The 4th configuration is the worst result from the eco-sustainability point of view. Such a configuration produces a quantity of CO2eq much higher than the 1st one, because it has a higher mass negatively impacting on the use and manufacturing. Thus, it is possible to state that, at difference of CNC machining tools, for die-casting process the imposition of the 2 constrains (minimum member size and draw direction) has poor influence on the sustainability.

It 's obvious that it is difficult for the designer to control all the implications of its choices when the goal is extended to the entire lifecycle of the product.

This integrated system of tools allows user to create multiple not conventional scenarios that clearly indicate which is the best route to take.

By a further sensitivity analysis conducted on each variant, the designer can decide which is the best compromise between the results obtained, considering performance and eco-sustainability requirements.

7 Conclusions

This work lays the foundations for an eco-design path integrating CAE tools with LCA aproach. This path includes different approaches for allowing designers to get useful information in order to create a more sustainable product directly in CAE environment. In particular, it has been shown how the introduction of a structural optimization tool into the ECOdesign process is a very useful tool, guiding also not expert designer to manage complex shapes and not conventional geometries. In order to manage them, eco-sustainability criteria have been opportunely interpreted for fixing objectives and constraints.

The peculiarity of the method proposed is that the modifications of the pieces are evaluated directly on the entire product life cycle. The case study has demonstrated how can be difficult for a designer control and manage all implications. The methodology helps designer to easily visualize the best direction, By means of guidelines, a set of design alternatives can be created and, representing them on a graphic, they can be easily evaluated. Once the best configuration is fixed, a deeper optimization cycle can be provided to the initial product following direction suggested by the method in order to achieve the maximum reachable benefit .

At the moment, the author are developing precise procedures for the application of the entire set of guidelines involving structural optimization tools and more in general others CAE tools. In particular the benefits reachable by adopting multi cycle optimization and multi-body optimization are under evaluation.

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Measuring the Results of Creative Acts in R&D: Literature Review and Perspectives

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Abstract. In their work on the C-K theory, Le Masson et al talk about the passage from R&D to RID, claiming that R&D in the era of innovation must revise its practices to adapt to the changes that have given birth to this new industrial paradigm. The authors speak of 'performance logic' as an incontrovertible step in this evolution without going any further into their thoughts on the matter. Only a few syntheses exist to allow us to understand the contributions that aim to qualify the inventive performance of R&D, this article puts forward an analysis and provides a literature interpretation on this subject. We then discuss three main points in accordance to what seems to us to be appropriate for the future metrics of inventive efficiency.

Keywords: Innovation, Inventive metrics, Creativity, Computer Aided Innovation, TRIZ.

1 Introduction

Whether it be physical or intellectual, man has always aimed to measure his performance. Today, this is even more so the case in the industrial world and especially within companies. Whether this is provoked by external factors or driven by a more personal willingness, performance measuring takes hold as soon as an individual desires to progress and to commit themselves to this thought process. Our industry already entered into an era of innovation over a few decades ago. Like all changes of era, industrial practices feel the effect of evolution and must themselves evolve with it. The impact of the arrival of an era of innovation inevitably ends in the future emergence of a norm that requires companies to adhere to a legitimate model from a superior authority (rather than a model that would only work for a given company). Therefore, innovation must be structured and organised within a company to go beyond the management and marketing speeches.

While innovation is the subject of much relevant research regarding its measurement [1], less research has found that the role of finding creative within it. This is mostly due to vague relationships between creativity and innovation. We decided to concentrate on the latter in this paper with a twofold objective: clarifying the fuzzy relationships between ideas, inventions and innovation and analyzing litterature on the creative side of design projects and its measurements.

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Currently, not many measuring methods are available other than productive performance, qualitative or financial measurements. And yet, this measuring requirement is seen in a growing number of companies regardless of their activity. To achieve this goal, it implies the establishment of procedures that of course target innovation, but which also reference notorious methods and tools so that a future norm can accept and verify the robustness and the reproducibility (or just simply whether it works) of the inventive capacities of a particular company. However, at present, very few tools (except those derived from creative stimulation such as brainstorming, 6 thinking hats or synectics) support the creative stages of project groups within companies.

1.1 The CEN389 Project

This future European innovation norm is not just a simple hypothesis; preparatory work for 2015-2017 has already seen the light of day and it reinforces the idea that an innovation measurement, even one that is difficult to set-up, seems inevitable [2]. Indeed, if the European Community decides to go ahead with the creation of a norm, one can easily anticipate that the industry will rapidly become concerned with the impacts and stakes involved with this norm. At present, this norm is conceived to be an innovation stimulant and the European Commission identifies 9 key actions which lead to the standardisation of innovation and which contribute to innovation in a very significant way as well as to the competitiveness of European companies. These include:

- Reaffirmation of the commitment to a standardisation focused on the market and the voluntary use of norms.
- Recognition of the importance of innovation norms, both formal and informal.
- The concentration of efforts on the elaboration of norms for the global market.
- To facilitate the inclusion of new perceptions in the norms.
- To improve the access to standardisation for all stakeholders (mainly Small and Medium-sized Businesses (SMB), users/consumers and researchers).
- To remove the obstacles which obstruct an effective application and use of the norms (the lack of visibility, complexity, incertitude on the norm conformity or even rival norms).
- To take into account the existing correlations between Intellectual Property Rights (IPR) and standardisation.
- To pursue the on-going reform process by European Standards Organisations (ESO).
- To take into account the evolution of European economic and social needs as well as the changes in international context, both economically and politically.

The desire to take this norm on board will invariably generate significant methodological and structural changes for a company. These necessary procedures also place the company in the best possible position to access new markets in the era of innovation. It is therefore preferable to exist in a market aimed at helping to affirm capacities by obtaining this norm. This can be achieved via the implementation of methods, indicators or even procedures. However, rather than waiting for the consequences of the arrival of such a norm, anticipating it seems to be a more promising strategic choice. Finally, as with all stages of evolution, all changes within a company are reluctantly provided. Yet, to accompany a company into the era of innovation in the direction of its own inventive and innovative performance as well as its durability is the affair of everyone within the organisation.

1.2 The DEFI Project

We have fixed ourselves an objective: to contribute to these changes by involving some research in a project entitled under the acronym DEFI. This project has a goal: firstly, to understand and to characterise the notion of Inventive efficiency of Design activity and then to elaborate on the means of measurement of this efficiency in order to finally succeed in adopting an indicator that helps companies to locate their R&D collective inventive capacities. Subsequently, companies which use this indicator can initiate the required actions to evolve in the desired direction, notably by accepting to evolve in their individual and group practices.

The measure of inventiveness in industry has very little, until now, been the focus of research. Only studies of performance measurements regarding routine design have been focused on. These studies provide usable indicators of after-the-event measurements whereas an activity that has been on-going must perform a "continuous" measurement. Nevertheless, one must agree to perform a synthesis on the existing contributions that conform to this ethos. This is the aim of the next section.

2 Literature Synthesis

An analysis of the existing literature on the subject of associated metric measurements of the inventive act in Design allows us to put forward several contributions. These contributions are formed from 3 different angled approaches of creative metric measurement: economic, productive and quantitative.

The economic approach: Using an economic approach we understand the financial measures and in particular the investment in R&D. It represents the funds invested by the company in its R&D department or projects. This indicator is appreciated by economists and managers because it allows us for a functional R&D expenses comparison between companies [3]. It also shows the importance accorded to innovation by the company and its desire to innovate [4]. Also note that the data concerning the R&D of companies have always been used as an indicator of innovation [5].

R&D expenses for example, are an investment; they create a durable input that in turn creates innovation. All this provides us with a measurement of capital that represents R&D. The latter becomes an indicator, not only of the presence on an innovative activity, but also it is more appropriate than R&D expenses on their own [6]. Adding to this, this indicator remains simple to implement and easy to estimate and its regular use improves, amongst others, the comparison between the different studies from the same company.

Concerning the time invested into research (including the time invested by the executives) this is an indicator used at the very first stages [7].

The productive approach: This measure is an evaluation of the results having a particular outcome. We found the following indicators: The number of patents requested and obtained, the patents citations indicated in the project and finally the time invested in research, i.e. the time spent by an engineer on a project. The number of patents conveying a quantitative measurement whereas the patent citations convey a qualitative measurement. The greater the number of patent citations, the greater the impact.

Lasting several years, patents as well as citations are an excellent method of inventive measure [8]. The patent is used as an indicator as it protects an idea, product of new mechanism, as a result we can ascertain the creative, inventive activity.

Patents are generally used as a database to create intellectual property indicators, but they can also provide indirect indicators of the efficiency of innovation investments [9]. Different approaches have been put forward shed light on the value of a patent. We find the patent citation to be an indicator of impact, the renewal fee which measures the value and data on the families of patents when the patent is introduced into another country (country where the patent is valid). A last value used in patents is the number of citations in the patent; this number is sometimes associated to its novelty level.

Another advantage is the availability of information (the fact that they are publicly released) and the formalisation imposed by the international authorities governing patents. This rigorous formalisation and availability are undeniable assets in semantic and syntactic research associated with patents.

Work which attests to the pertinence of patent citations as an invention or innovation quality indicator (in terms of the correlation between the internal subjectivity of the evaluation of the importance of patents by technical specialists and the number of patent citations) have already been the focus of several in depth studies [4].

Quantitative approach: This concerns the measurement of quantity and/or the quality of formulated ideas during a creative session. Here, we find indicators for the quantity of ideas per employee and the time spent on the creation/formulation of ideas.

The number of ideas per engineer per year is, for that matter, an indicator which can be used by a company during annual strategic planning. This approach sometimes has an objective to be reached for each engineer involved in the R&D department of the company.

2.1 Analysis of the 3 Approaches

In this section we discuss the limitations of these indicators to put them into the perspective of our research issues. Investment in R&D is, without a doubt, a pertinent economic indicator, but this only provides us with a partial vision of the research efforts. In fact, this does not take into account the informal aspects associated with R&D that often extend past the financial aspects to the engineer and scientific research aspects unique to the industry in question. This limitation is accentuated by the difficulty of recording in an accountable and financial way, the whole of the expenses assigned to R&D [10]. In addition, such an indicator does not discriminate the research carried out by the company in secondary domains and subsidiary technologies, as they target the company's global investments and not the technological objects which are more concerned with R&D [3]. Added to this is the limitation caused by SME's which do not possess an obvious R&D department. Such an indicator remains highly contested in literature on this subject, including economic literature. Kemp et al for example [11] affirm that the R&D studies under estimate the informal activities of small businesses.

In regards to patents records, we notice that not all new products, ideas or procedures are always patented [12]. Registering a patent depends on strategy and economic choice [8]. The problem linked to this type of indicator is that it is used in an essentially strategic goal and that not everything is patentable or patented [11]. Also, not all companies are necessarily capable of financially applying for patent [3].

Finally we conclude this analysis by the metrics surrounding the quantity of ideas. If we assume that at the beginning of the seventies there was a quantitative objective legitimised by the work of Osborn [13]. One point put forward by Osborn goes as far as to affirm that quantity gives birth to quality, thus the greater the number ideas the greater the chance of seeing creative ideas materialise. The other more recent analyses question these affirmations, notably that an idea does not express a degree of inventiveness and that the company is often powerless when faced with an over abundance of new ideas [14].

2.2 Measuring Creativity: Myth or Imperious Necessity?

Investigations into tests designed to measure the creativity of an individual have already been published as well as investigations into the management of creativity [15].

At the heart of these studies on this subject, creativity was perceived as a cognitive characteristic of artists or geniuses. For this reason its measure firstly targets the individual. The first models were therefore largely inspired from intelligence tests.

Three main categories can be seen:

1. Creative or divergent thinking tests [16].
2. Personality and biographic inventories: [17], [18], Creative altitude scale [19], Creative personality Test [20], "F" Test [21],
3. Measuring creativity according to 8 dimensions [22].

We then observe a need to distinguish the difference between those that reveal themselves as being creative producers and those that don't. So a notion of place and time appears and Kimberly et al push forward the idea that innovation can be new for the organisation implements it when it has already existed elsewhere. Companies are therefore interested in the measure of creativity, or rather its process, with performance being the goal. It is therefore simply a first concluding observation that the traditional methods of fixing objectives inhibit creativity. Researchers who lean towards this theme conclude that creativity cannot be managed and that the desire of companies to develop and drive managerial actions in favour of creativity inhibit it more than they favour it.

To support their affirmations, these authors put forward the idea that is it most necessary to understand what favours creativity in the heart of organisations but nevertheless creativity always resides in the personality of the individual. In addition, their interactions and the environment within which these individuals evolve determine their creative behaviour [23].

Another older notion put forward by Ford indicates that routine actions are the priority for creative actions [24]. A company that faces problems, regardless of their origin, will logically favour routine actions. They also put activities of a creative nature aside as in these conditions routine actions seem to guarantee security and survival.

We finish with the reluctances of creative measure; creative phenomenon does not correspond to that which a measurement imposes, because the measuring tools are in opposition with the essence of the creative process. This immeasurability is explained by the fact that by wanting to measure the fruits of the creative process we are looking to measure the unknown. A metrics measurement will only make sense when the process has been mastered. It shows that the creation of measuring instruments dedicated to the creative process cannot be profitable to the company because their use is not predetermined nor guaranteed.

Other more recent studies did not share these reluctances towards the measuring of the creative act. Among the most successful were Hernandez et al who put forward not only the notion of inventive efficiency measuring but also presented some interesting leads [25]. They observed and noted certain components unique to creativity that seemed to posses the pertinent attributes of the act of generating ideas including:

- The aptitude of stimuli provocation;
- The capacity to suspend judgement;
- The flexibility of representations;
- The aptitude to change reference system;
- The rapidity of incubation;
- The association to examples.

They then tested each of these particular traits in order to observe the individual's aptitude of possessing them. The measurement associated with this observation is divided in to 4 experimentally independent variables (quantity, quality, novelty and variety).

3 Perimeter of Our Action

We have seen different approaches that are sometimes conflicting in their perception of what is a creative act. However, before we look at 'what' and 'how' to measure, we asked ourselves the background of question of why we want to measure it.

At a glance the terms 'idea' 'innovation' and 'invention' are often perceived as synonyms whose edges of definition are sometimes blurred. It therefore seemed important to clarify the boundaries between these terms in another way other than by definitions upon which multiple pre-existing definitions would pile up and add confusion. So it is therefore by a schematic classification (namely the 3I) that we illustrate our subject.

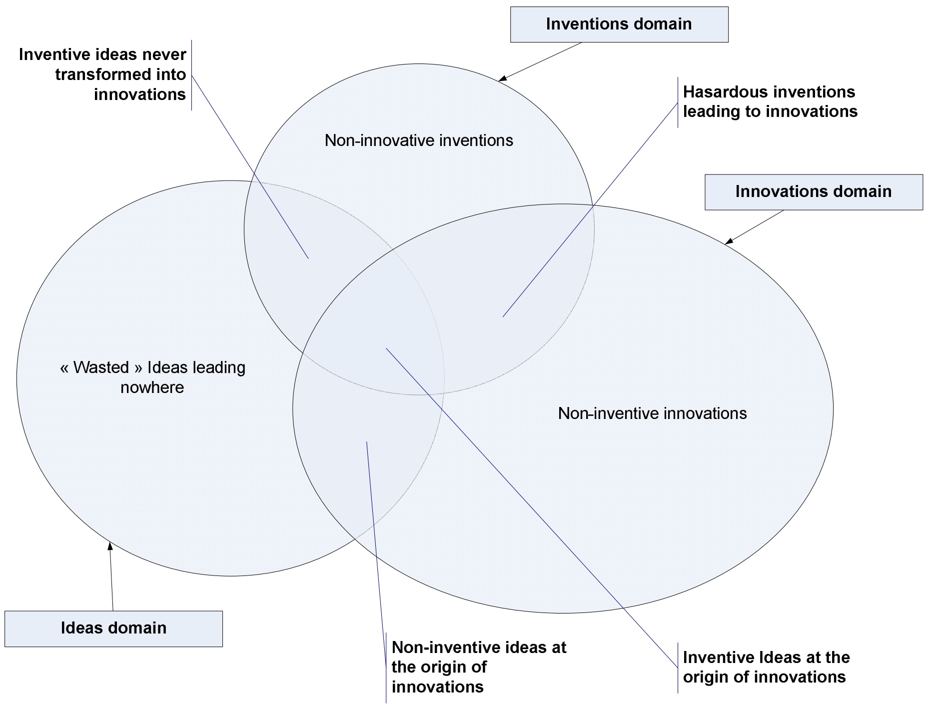

Fig. 1. 3I diagram for clarifying objects' fuzzy relationship with ideas, innovation and innovation

The chosen representation is composed of 3 spheres which represent the 3 basic "domains" (figure 1), i.e. ideas, inventions and innovations as well as their interactions:

- The idea sphere represents the intangible fruit of the imagination (structured or not) of the individual in the phase of concept generation.
- The invention sphere represents the plausible material aspect from the creative act, the new artefact that seems to be constructible but on a non-commercial basis remaining in the prototype phase.
- The innovation sphere that symbolises the encounter between an inventive proposition and a market that accepts it as new and plebiscite (sign of success).

Each sphere possesses a specific zone as well as shared zones and so offers interactions of particular significance:

- Inventive ideas represent not only the promozing ideas of innovators but also those which had not had market success.
- Innovating ideas are not only pioneering but also have market success.
- Innovating idea are ideas generated by improvisation (have not been subject to a particular problem solving attempt) and which have seen (by chance) success in the market.

In our case, we accord a particularly high importance to the interconnection of these 3 circles, i.e. the inventive ideas of which the innovative vocation has been proved. The surface connection of these 3 spheres is certainly qualitative but it illustrates the meaning of our subject. The reality of the market shows a more significant section of non-inventive innovations. The 'wasted' ideas are obviously dominant, whereas the small percentage of inventive ideas that result in innovation is a minority. This could be explained by the fact that inventions often create a significant breakthrough and the market is not yet ready to welcome the invention (absence of need or need not yet affirmed). We could therefore imagine that the capacity of an idea becoming an innovation would be inversely proportional to the degree of inventiveness.

To give an example to better explain this image we try to discuss several products which are known to the general public and we target their possible localisation in this diagram previously mentioned.

- **Iphone:** This Smartphone is marketed as a collection of innovations but to locate the object as a whole we must divide it up into certain components. The 'multi-touch' technology for example is already registered (therefore known) but not yet applied to mobile telephones. This could be an innovation because it stems from a non-inventive idea resulting in innovation. For its part the purchase of on-line applications is an innovative invention because it stems from a pioneering procedure, radically new, gaining notoriety in the domain and accepted by the target market. On the whole, we place the Iphone in the category of inventive innovations mainly due to its strategic software, marketing and communications more than for its hardware strategy and fabrication process which is essentially composed of solutions resulting in non-inventive innovations.
- **The Dyson vacuum cleaner:** For the first time, an inventive solution (using the 'vortex' technology (to separate air from dust and so to relinquish the bag during aspiration)) reaches its technological maturity to the point whereby it is released with success on the market. It is an innovative invention. We add also the particularity that the CEO of the group acts as the publicity icon during television advertising. This procedure is certainly an innovation, but non-inventive because others before him have already done this (Alain Afflelou or Luciano Benetton).
- **The water Motor:** Is an inventive idea as it relies on valid scientific foundations, but the technological maturity does not allow for the general public diffusion that could have granted it innovation status (no market success).

We now look at engineering projects of students in their last year of engineering curriculum. They endorsed a module namely "Inventive Design" (majorly supported by TRIZ tools). The starting point of such an approach is to invent the future of a currently existing object which targets the evolution trends of TRIZ and the solving of contradictions. The situation of engineers' project analysis is interesting and dissociates from an after-event-analysis such as those we have already mentioned in the last paragraphs. Indeed, it is easy to estimate the impact of a product known to the general public on a market after its launching. It is more difficult, but also more challenging to observe the fruits of an inventive project that has not yet attempted to be released on any market. The following objects have been analysed in order to identify their possible localisation in the 3I diagram:

- **The kettle:** The proposed improvements are to make the system more water tight to increase the internal pressure and so favour a rapid increase in liquid temperature. One of the solutions envisaged by the group is to put the water in motion (like vibrating the heat resistance) to create a convection movement and so allow the water to heat more quickly. Finally, a separation of systems in order to only transport the packaging and not the whole system in concerns for weight and manageability aspects. When we look at these improvement propositions in themselves they are not inventive as they already exist for other systems, but their application in this case could be revealed as innovative if we base it on the novelty of domain application. We estimate therefore that the proposition of the kettle is a weak inventive proposition with the vocation of becoming an innovation (as the success of societal acceptance cannot be measured until afterwards).
- **The Fins:** This team proposed the use of a shear thickening material (that hardens on the mechanical shaking action that puts the fins into motion) in a tube that covers the fins of the flippers in order to optimise muscular effort. Such a concept is very inventive as it generates a significant technical break through on the basis of a real physical concept (thixotropy), however, whether it will gain societal acceptance that would lead this invention towards innovation status is still very uncertain. We are therefore more so in favour of an invention for which the innovation status is still unclear.

While evaluating the impact of a product (or an intention of product) in terms of its innovative potential has been at the heart of several researches [26][27], we have tried to highlight novel component of an evaluation that were in our mind missing for a more relevant metric of inventiveness. In that regard, two sub-metric measurements are to be considered:

1. That which qualifies the degree of inventivness. Like Altshuller who identified it by observing the distance between the origin of the solution with the origin of the invention and the domain within which the initial problem belonged to [28]. We can therefore talk of invention in different degrees (5 according to Altshuller) before giving hypotheses on the future of these inventions.
2. That which qualifies the reliability of the potential innovation. The aptitude according to which an invention has the chance to become an innovation, to minimise the risk associated with the incertitude of market success [29]. In this sub-metric measurement we can also bring forward the incertitude associated with the scientific and technical reliability of the idea. In other words, does the idea seem in itself scientifically plausible or is there a long way to go before we can rely on it without too much of a risk?

4 Discussions

In this section, we wish to highlight some existing tool materials and techniques in support of the creative act in Design. The goal is to explain the reason behind that which exists does not allow us to assume the metrics of the creative act imposed, as explained in the last section and that deeper investigation into this subject is necessary. Certainly, attempts can sometimes make the news, announcing new techniques proposing different and original approaches. It is therefore necessary to observe them in order to estimate if they resolve in part or its entirety the problems exposed. Last, TRIZ has been undeniably a key word repeated again since two decades in a recurrent fashion in the industrial, scientific and methodological world. We have devoted a significant part our discussion to it.

4.1 Brainstorming Reaches Its Limit in the Era of Innovation

The findings on the inefficiency of brainstorming in the current context of innovation exceed themselves. More broadely, creativity sessions in general are pointed out as unable to adress problems' complexity of the current industrial era. Besides this, creativity does not obey any rule, principle or even law; it can therefore difficultly be obtained "on demand". To attempt to dope creativity by asking too much of the human brain exposes us to the risks of an under performance as all that it (creativity) 'occupies' risks being inhibited. Stroebe and al in [30] proved that the rules of brainstorming (to favour the quantity of ideas, to encourage unusual ideas and to discourage criticism) is suitable for the production of ideas but that brainstorming delivers the best results when the groups have not had any pressure from management. Mullen et al in [31] presented a loss of productivity when brainstorming was practised by large groups. They therefore favour the use of this technique on an individual scale or in a group of two people. The problem faced is the expectation of the participants concerning voicing their opinions and so slowing down the enthusiasm surrounding the production of ideas.

However, the era of innovation demands go beyond the search for quantitative performance. The deliverable ideas from a creative session are provided more quickly for a reduced number of concepts and emerge as a very small number as they have already been trimmed down, for example, by the precise questioning of the wording of the objectives. The whole thing preserves the inventive aspect of ideas as the pool of reflection goes beyond that of the restrained circle of individuals capable of investigating.

4.2 TRIZ Emerges as a Potential Lead but Does Not Impose Itself

The novelty of the approach proposed in TRIZ very quickly seduced the large groups with the originality of its foundations and the rigour of its implementation. Whereas other tools seem mainly correlated to individual or group creativity, techniques derived from TRIZ seduces by their apparent capacity to broaden the field of possibility in the search for structured solutions. The fact that existing software tools come in support of its implementation is also a factor that favours its use in the industry.

Yet TRIZ will have its share of obstacles concerning its integration into companies. Indeed, to use it in a trimmed down manner [32] it is hardly even necessary to control the slightest of details in order to be able to provide the solution to multidisciplinary and complex problems. A significant training and often a change of mind is essential.

Whereas some people see TRIZ as an 'invention machine' [33] a realist observation makes them understand that its use calls into question significant structural and organisational handling within the practices of a company and that all changes in the industry are often accompanied by disagreeable difficulties.

However TRIZ was described by Alshuller as a theory, its potential methodological potentials are almost infinite. One can therefore legitimately think that the original and theoretical aspects developed by Altshuller (notably the concept of contradiction and the notion of evolution law) could be noted as fundamental to the reconstruction of new industrial practices adapted to the problems of the era of innovation. However, bearing in mind what the professionals from the world of TRIZ have up until now produced, nothing emerges in a legitimate way as if it was the model for the whole industry to follow.

However, several study findings have demonstrated the aptitude of TRIZ to be more prolific that other methodological approaches concerning its pro rata of inventive ideas in comparison to the quantity of 'waste' ideas [34]. Where the other approaches concentrate on the quantity (Osborn model), TRIZ focuses on the guarantee of the inventive aspect of a concept before accepting its presence on a list. However, every concept must make sense of the given contradiction engaged in resolution, which other approaches don't do; they fully unleash the act of ideation, accumulating more waste ideas more than those which effectively resolve a problem. Finally, adding the necessarily unpredictable side of the classic creative approaches, contrary to TRIZ that organises itself in a pragmatic way and issues all its potential in the time limits which are correlated to the complexity of the problem to be resolved, but all the same, are estimable beforehand. Today, companies find themselves restrained to reducing the cycles linked to projects in order to increase the number and their competitiveness. One easily understands that an approach based on the unpredictable rapidly reaches its limits in such a situation.

In a comparative table, Fantoni et al put forward an important point: only TRIZ systematises the use of a vast basis of multidisciplinary knowledge [34]. This allows us to use tools or methods designed to:

- Reduce the incertitude by relying on existing data;
- To systematically organise thinking out of the box of what is known within the company (or the study group) and so favouring the growth of the value of inventive ideas.

To help companies correctly choose the most adapted tool, Fantoni et al have performed a class system of problem resolution methods. They have selected the methods the most widely available in not only the industrial world but also in the academic world. Their first analysis covers the force of the existing links between a given method and the different generic steps of a Design project. Each method is attributed a value between strong and weak to qualify these links. As a matter of fact no method is ideal but TRIZ (envisaged here under the angle of a method) finishes ahead in this comparison.

A second comparison puts forward the essential expected characteristics of a method and a measurement in accordance to 3 values is performed (yes, no and a mean value). Once again TRIZ comes out first as the only method having obtained a positive value for each characteristic. This study shows that TRIZ seems appropriate to inspire the construction of new methods aiming at satisfying the engineers faced with their Design difficulties in the era of innovation. Nevertheless, the paradox persists; while way ahead in comparison to other approaches, TRIZ in its current shape does not convince industrialists sufficiently to adopt it. Hence a questioning appears as a perspective of future works: which role could TRIZ have in the construction of a new method to make company R&D practices evolve?

4.3 Three Leads for an Inventive Design Efficiency Metrics

On the basis of the literature analysis and the trends on the subject of creativity metrics we observe the finding that brings the communities together: everyone agrees that it is legitimate for a company to aspire to measure it creative capacities. Certain work then shows why this is not possible, other attempt to contribute to this problem by being a strength of proposition. In the DEFI project described in the introduction of this article, we fall under this second circle of influence of contributors, in keeping in mind the legitimate reluctance of researchers that are opposed to the measuring of creativity. The three main outlines of our work are based around 3 points that are firstly aimed at redesigning the perimeter that is seen by avoiding the trap of measuring the fruits of the human mind. We consider that the company group acting as a team for whose results exceed the simple sum of individual performances.

In the next section, we define our orientation of research for a company inventive capacity metrics.

Point 1: Favour the production of "inventive ideas" versus "ideas of any kind"

If the envisaged production of ideas under the angle of quantity is not the priority, the objective of rapid emergence of these ideas seems more legitimate. An adapted metrics system must therefore observe the fluctuations in creative production results by estimating the time lapse that separates the instant where the problem exists from when the solution arose. In the same way, the regularity of a performance is proved at the end of an investigation (or miscellaneous solicitations); it attests that the group of agents involved control the creative process with more or less ease. So as not to bias such a measurement, the inventive value of solutions cannot attest to a success alone. This is because it would be easy to remember only the released ideas and those imagined in use in the invention. The ideas which must be considered as a solution is not every possible idea, but only those that focus on the developmental decisions, i.e. those that the company would focus R&D expenses on.

Point 2: Favour the "collective pugnacity" for transforming inventions into innovations

The settings of our thoughts is focused on the breakthrough projects, these project are exclusively covered in the measurements. The routine projects, for their part, will not intervene in the invention metrics. However, when a company's product requires open reflection on invention, the capacity of all the agents responsible for creative productions must let their aptitude come forth so as to accept what is routinely released by the company, not in a risky way but in an opportunistic way. The refusal of risk and systematic reflex is to distance yourself from it, to go back to the reassuring aspect is in no case inventive and should be estimated in the inventive metrics. It is the regularity with which a company (via the intermediary of its agents) accepts to face the unknown within its R&D department which could be a significant component of inventive performance.

Point 3: Do not under-estimate the difficulties linked with adoption

In addition to the creative production performance aspects, a measurement only makes sense if it qualifies an aptitude associated to the outcomes of the company. Yet, the company must reach its target market with success in order to prosper. Only the inventivness of concepts would not be estimated, one must add it to the impact of the group that represents the whole chain of company agents, from the manager to the operational staff and their confirmed desire to act as a team for the success of the inventions. However such a measure, as it is not certain until after the event, cannot rely on the shifted observations over time. It is in that instant that an invention metric must serve to indicate the capacities of the company, and not on the basis of past success stories. Such an indicator (stakeholder of a more global indicator upon which we are working) should observe the decisional chains of the company as a flow through which we must estimate their capacity to encourage inventions.

5 Conclusions

The scientific literature on the subject of measuring the creative act's results is abundant. Two contributing scientific domains stood out. Human and social sciences, more precisely cognitive sciences, which show the products of the mind and analyse its mechanisms and the climate within which it is most opportunistic to place the product. Managerial and economic sciences, which focus on the organisation, nature, typology and contextual reason (financial and market) prove to be efficient in the matter of innovation. In this article, we expose a point of view that reveals engineering science by focusing on the R&D actor, the project and the company within which its activity is registered and the scientific and technical value of its cognitive productions conveyed by resolved problems pertaining to the object conceived.

This article is a preamble to a future metric of inventive efficiency by carrying out a synthesis and by analysing the literature on this subject. We then adopt a particular point of view and expose it with a discussion section through which we also present how we will organise the future research on this subject. Three points, where a measure is necessary have been defined and discussed. They constitute three major outlines of this research. To indicate that which must be observed, the context explains the positioning of an available artefact on the market or the fruits of an R&D design project according to the 3I diagram. This allows us to come to terms with the complexity of qualifying a new idea and indicating its status (from a wasted idea to an inventive idea leading to an innovation).

To finish, our article explains that the arrival of techniques derived from TRIZ on the scene of creative tools gains popularity from companies but only brings partial enlightenment to level out the cognitive, social, managerial and procedural difficulties of the company when faced with its desire to innovate. This last component is therefore promising in terms of it foundations and will be useful to take into account during the stages of inventive progress of a company. However, an efficient legitimate indicator in the industry will see the light of day and there is still a substantial distance to go before we achieve this.

Yet, the arrivial of the CEN389 project from the European Community replaces the challenge of invention measuring which was at the forefront of the industrial medium term manager's and industrial researches preoccupations. The immediate consequence of this project is that the measurement of the creative act which was described only as a utopia a decade ago has now become a legitimate object for which pragmatic results prove to be more than necessary.

Acknowledgments

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Methodology for Knowledge-Based Engineering Template Update

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Abstract. This paper addresses the problem of knowledge templates update in product development. A framework is developed to support template instances update process by providing a decision support system and an update strategy. An Issue-Based Information system is designed to allow the collaboration among various experts in order to solve template related problems. An ontology is used to represent and to reason on knowledge about templates, products and their relations. This allows the construction of an update sequence for the template's instances as it provides an efficient overview of relationships, even implicit ones. The proposed framework fills an actual gap concerning template updates, which slows down templates adoption for large scale industrial use.

Keywords: Knowledge-Based Engineering, Knowledge template, CAA V5, CATIA V5, Update Strategy, Ontology, Issue-Based Information System.

1 Introduction

Nowadays, high-tech industries such as the automotive or aerospace are designing products that are more and more complex and that integrate various disciplines. This has lead to the emergence of collaborative platforms that allow several engineers or teams to work efficiently together on a project from distant places. Collaboration is a key to successfully release a product in time and with a high quality [1]. Several collaborative platforms have been developed to support cooperation using Web technologies to improve the integration and interoperability of remote users [2, 3].

However, having several persons with different points of view is a source of conflicts and misunderstandings due to, for instance, differences among domains' vocabulary. One solution to solve this problem is to formalize the technical terms of each domain and to create correspondences among concepts defined within each domain. This can be achieved by defining an ontology of the domains. An ontology allows to represent concepts and relationships between these concepts [4] that can be used to both infer implicit knowledge and to check the consistency of the domain definition by resorting to an inference engine [5].

Beside collaboration, another key factor in modern product design is the ability to reuse existing knowledge in design, products or processes. In this scope, one major change during the last years is the democratisation of Knowledge-Based Engineering

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(KBE). KBE is a large field at the crossroads of Computer-Aided Design (CAD), artificial intelligence and programming.

1.1 Knowledge-Based Engineering Templates

Knowledge-based engineering templates are "intelligent" models or features that are able to store design intent and product design knowledge. They can then restitute the knowledge by adapting them to design contexts, i.e. environments where the template is used, such as a car assembly model or a wing model. This paper focuses on the product design where templates can be of several kinds: models, features, etc.

Templates are parametric models designed with KBE elements such as formulas, rules, and automation. KBE elements allow a modification of the template content (e.g., configuration or geometry) according to given inputs. The process of putting a KBE template into a specific context is called "instantiation" and results in the creation of a copy of the template that will be put in the given context. This copy is called an "instance". According to the inputs, the instance will be configured to fit the specific context. Instances have a separate life cycle, which means that any modifications made to the template definition will not modify its existing instances.

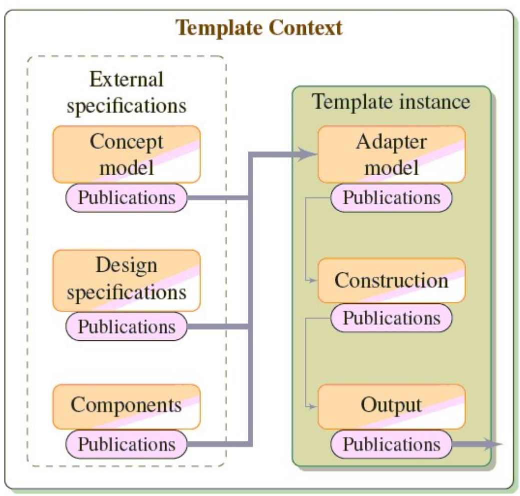


Fig. 1. Generic structure of a CAD template instance in a context with link flow

Figure 1 presents a generic view of a template instance in a context. The structure of a template definition (and of an instance of this template definition) is composed of three main elements:

1. an adapter, which gathers the inputs and contains basic geometry information that will drive the design of the template,
2. the construction, which is the core of the template and that provides the functionality of the template (geometry generation, calculation, etc.), and

3. the output, which contains elements (geometry, parameters, etc.) that are provided in order to be referenced by external elements located in the context.

The inputs of a template instance can have various sources, which can be the geometry of other models, design specifications or external documents like spreadsheets. The references between elements should be established through output publications, which can be considered as the output interface of an element. The publications provide a named visible reference of an internal element of the document that can be easily identified and referred to. Furthermore, publications preserve the links in case the contents of an element are replaced.

1.2 Template Update Issues

The template life cycle (figure 2) is an iterative process. Before a template is deployed to end users, it has to be designed based on the requirements, tested, and packaged with the necessary documents (documentation, configuration spreadsheets, related CAD models...). Once deployed, templates are maintained and updated in order to fix possible bugs or to add new functionalities.

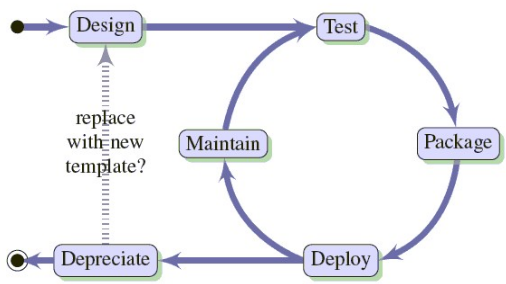


Fig. 2. Knowledge template life cycle

In large and complex assemblies like cars or airplanes the number of templates and template instances can reach several thousands and even more. This implies a huge effort to maintain them as they become more complex by incorporating new potential variants for future design [6]. Because several expertises are involved in the design of a product as well as different points of view, conflicts are very probable. The resolution of these conflicts needs a tool that allows remote stakeholders to propose their ideas. Then the solution coming out from the consensus can be implemented into the template and will give a new version of this template.

When a new template version is available, there is a need to update the corresponding template instances with the new definition, so that it can take advantage of the modifications and the same version is used everywhere in order to ensure the consistence of the instances with the corresponding templates. This synchronisation between the templates and their instances is not fully handled by current Product Data Management Systems [7] and the impact of the modifications needs to be evaluated by hand. When working with large assemblies containing several thousands of template instances, finding a feasible strategy to update them all is a challenging and time consuming task. The complexity of the relations network in KBE assemblies complicates this task as the order in which instances are updated has a significant impact on the result and might generate time-consuming redundant updates. Relations between documents need an efficient visualisation tool in order to have an overview on all interdependencies [6]. Furthermore two categories of template instances were identified: the direct and the indirect instances. The direct instances are resulting from the instantiation of a template. The indirect instances are the result of the copy of a template instance included in another template.

The application of template modifications to their instances is a difficult and time consuming task. Engineers have to analyse assemblies and relations to estimate which documents have to be updated and then make the updates. Thus this task can lead to errors due to the complexity of the assemblies and relations. To efficiently achieve this task, an update strategy is needed in order to avoid redundant updates or to prevent forgetting one update.

The problem of template management was addressed by only few research activities in the past e.g. the management of templates [7]. The proposed solution was a business process that involves ontologies that are used to represent knowledge about templates and their interconnections. An ontology is created from each template by mapping them to the knowledge model. Each ontology describes the inputs, outputs of the template and interconnections with other models. So the changes made in one template can be propagated to other templates by using the relations described within the ontologies. However his approach focuses on templates to template relations and engineers still have to navigate the ontology to find dependencies.

In order to improve the update process, this paper proposes a framework composed of an ontology-based decision support tool, and an ontology coupled with an algorithm designed to compute a sequence of update tasks for the update of template instances.

2 Update Process

The process depicted in figure 3 was elaborated in order to guide the users of the methodology in order to solve template issues and perform template instances updates.

The proposed process covers major aspects of template update, from the cause of the modification, to updating the instances. The process is decomposed into three subprocesses, which are marked (a), (b) and (c) in figure 3:

The aim of subprocess (a) is to allow the decision making process to take place in a collaborative environment, concerning the template issues or new requirements. The modifications applied to a template should then be documented and stored in the system for further use.

The subprocess (b) starts after the template update, with the aim to keep an up-to-date knowledge base about all documents involved in the product design, which are models, catalogues, assemblies, their relations and the templates. This knowledge base provides a comprehensive overview of the dependencies between documents, which will be used in the following subprocess.

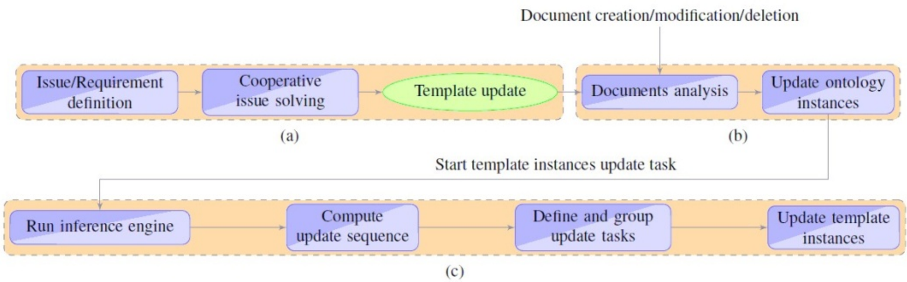


Fig. 3. Proposed global process for template update

The subprocess (c) is triggered according to company criteria (time, manpower, nightly processing, etc.). The objective of this subprocess is to support engineers in the template instances update tasks by providing them a sequence of necessary updates to follow. By doing this, the complex manual task of identifying the elements that require to be updated is avoided.

3 Decision Support and Design Rationale for Solving Template Issues

3.1 Issue-Based Information System

This section describes subprocess (a) of figure 3 which helps designers with different competences to collaboratively develop suitable design solutions. Decision support systems are already used in several domains such as design processes [8] or process planning [9]. The proposed approach is based on the Issue-Based Information System (IBIS) framework. IBIS is a generic argumentation-based framework for problem solving, which allows several stakeholders to propose their own positions about an issue and then argue about all the positions.

The IBIS framework can also be categorised as a design rationale (DR) tool [10], which represents and stores the decisions, the argumentations and the alternatives behind design choices.

The IBIS framework has been extended in order to solve template issues and to support further tasks such as the template instances updates in the subprocess (c).

3.2 IBIS Extension

The IBIS framework provides the basic elements to support the collaborative solving of complex problems like template issues in this case. By storing the process and the choices that have lead to a design solution, it also endorses the role of a design rationale solution. The IBIS framework has been extended with new concepts from the product design in order to store the knowledge specific to template updates.

An extension of the IBIS framework demonstrated on a CAD template application has been presented in [11]. The IBIS model is specialised in order to integrate the link flow aspects, which are relations between templates and other documents. The aim is to allow the documentation of these relations to provide CAD template designers as well as CAD template users with useful information that will allow speeding up their respective processes.

The structure of this system is implemented with the Web Ontology Language. The Web Ontology Language (OWL) is a knowledge representation language based on open standards and aims at defining ontologies by allowing the formal definition of their concepts and properties. OWL allows using reasoners on knowledge in order to automatically classify the knowledge and inference engines to discover new knowledge. The current work uses OWL-DL, which is a subset of OWL based on description logics [12], which provides the best expressiveness while preserving computational completeness.

4 Knowledge Representation for Templates and CAD Models

By following a right update strategy, engineers will not need to look for template instances in the assemblies and will be informed about the documents that can be impacted by instances updates. The strategy is provided under the form of a sequence of updates to realise. To generate an update sequence, the algorithm requires information about the documents types and the existing relations between documents. To provide this information in a computer understandable and processable format, an application ontology has been developed that is represented in OWL. An ontology has been chosen because it allows the classification of knowledge and the use of inference engines to infer implicit knowledge, i.e., not provided by the documents but known by the designers.

4.1 Case Study

In order to define an ontology that can be used as knowledge base to compute update sequences, an analysis of the template update process is needed. For this purpose, some template applications within CATIA V5 (a Dassault Systèmes CAD system) were analysed.

CATIA V5 integrates KBE workbenches that provide mechanisms to create and instantiate KBE templates. It is also possible to use standard CAD models as templates without resorting to a specific workbench. However with this method, there are no explicit template definitions and no support tool for template instantiation. The result of the instantiation with both approaches is the same, it is impossible to distinguish the template instance resulting of a standard model from an instance from the CATIA V5 Knowledge Template workbench.

Regarding relations between documents, 19 different types of links have been identified. Each link involves two documents, one for the source and the other for the target of the link. Links are used to refer to, or use an element contained in another document. Hence some links have an impact on the update propagation.

For instances update, the users need to locate them, as there is no tracking mechanism. Once they are all located, a rank must be given to each of them in order to establish the order in which they are to be updated. This rank should be estimated under the consideration of the relations between documents. Engineers can then address the update itself by taking care that the elements referencing the instances are updated too.

The analysis on template update shows that several factors impact the instance updates: the document and template types, links between documents and the order in which the instances are updated. We propose to represent the domain with an ontology to obtain an overview of relationships and allow an automatic processing,

4.2 Ontology Description

The aim of the ontology is to provide a classification and an overview of the document types and all explicit and implicit dependencies in templates and assemblies. This phase corresponds to the subprocess (b) in figure 3.

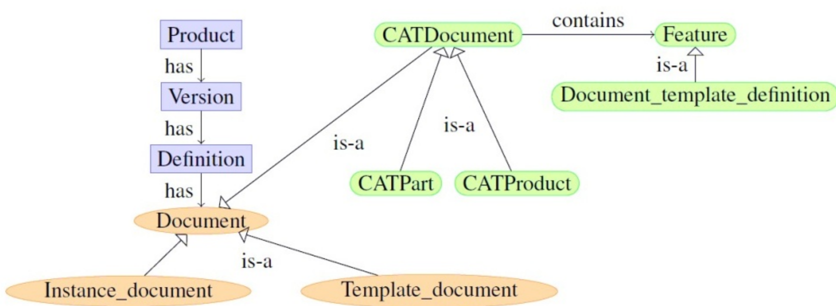


Fig. 4. Extract of the ontology presenting the concepts with the abstraction level (left) and the CAD system concepts, here CATIA V5 (green rounded rectangles)

An application ontology composed of three levels (see figure 4) was created, that features a top-down as well as a bottom-up approach. The top level (rectangles) contains the most general concepts that were taken from the STandard for the Exchange of Product model data (STEP): a product has several versions, each version is composed of several definitions, and each definition owns a list of documents. This level aims at laying a solid basis for the representation of products with their versions and definitions.

The third level (rounded rectangles) contains all CAD system specific concepts. Concepts presented in the figure are defined according to those in CATIA V5. For instance the “CATProduct” concept represents documents defining a product and thus has attributes like name, location on the file system and so on. In CATIA V5, the definition of a document template is a features contained within that document. There are also feature templates that represent, for example, a predefined hole with its possible diameters listed in an external spreadsheet document. These concepts will be later instantiated with the data coming from the automated analyse of templates, assemblies and their related documents such as drawings.

Finally, the mid-level (ovals) realises the link between the first and the third level. In this level concepts, which are the core of the presented application, are defined: template, instance, document, etc. Their aim is to provide genericity to the presented approach in order to be able to address various CAD systems. With these defined concepts, a more comprehensive and detailed representation of the domain is achieved. The three levels present in the proposed ontology are connected together with different properties like “is-a”, “equivalence” or “aggregation” properties.

Link types, represented as a relation in the ontology, have also been classified and problem specific types have been added. For instance, the “propagation link” has been created that group CATIA V5 links that impact the update of instances. This allows enriching the link classification and to formalise the implicit relations like reverse links, which will thereafter be instantiated by the reasoner.

The designed OWL ontology provides a comprehensive overview of elements present in the target domain. The FaCT++ reasoner [13] is used to classify the knowledge and also instances of the third level into upper levels concepts. All this knowledge can now be used to automatically build sequences of updates that will save time to engineers in the template instances update tasks.

5 Update Sequence Computation

The process of updating of template instances is triggered according to company criteria, such as every week. This is currently a task mainly achieved by hand. The aim of this work is to provide the engineers with a comprehensive sequence they can follow. This step corresponds to the process presented in figure 3 (c). Following this sequence will save time, as the engineers do not have to analyse the status of assemblies with all their complex interdependencies.

5.1 Approach

The documents and links can be represented as a directed graph where each document is a vertex and each link is an edge. The specificity of the obtained graph is that nodes and vertices are typed. Their types depend on the concepts and relations in which they are classified in the ontology. Represented concepts are those from the middle level of the ontology. Hence, the CAD system is abstracted in this representation. One node can have several types as documents can be classified under several concepts. The proposed algorithm works on this graph to extract relevant nodes and to assign them a rank. The objective of the ranking algorithm is to build an ordered sequence.

5.2 Sequence Construction

In order to construct the ranked sequence, an approach based on hierarchical structure visualisation and directed graph drawing was designed [14]. These allow an efficient organisation of vertices according to their relations with other vertices. The algorithm they proposed is composed of four phases:

1. Place the graph nodes in discrete ranks.
2. Order nodes within ranks to avoid crossing edges.
3. Compute the coordinates of nodes.
4. Compute edge' splines to avoid nodes.

This paper focuses on the first phase, wherein nodes are ranked. The proposed method builds a hierarchy composed of n levels, from a directed and acyclic graph.

This algorithm has been adapted to the template instance update problem. The graph represents concepts as nodes and links as vertices. The classification realised in the ontology presented in section 4.2 is used to evaluate if the node has to be taken into account or not. The impacts of the link are defined in the ontology through the classification of the various links types.

Specific behaviours are implemented depending on the types of the documents: for example if a document is a template, the behaviour needs to be adapted because templates may be composed of other documents or instances that have to be up-to-date before updating the template's instances. Otherwise, the elements that replace the instance will not be up-to-date and may require additional updates, which is something that should be avoided.

Providing a sequence of updates for template instances in an automatic way avoids the time consuming task of preparing it by hand, as well as it reduces the possibility of making errors, redundant updates, and forgetting some instances. The computation of the update sequence is simplified by the use of the knowledge present in the ontology. Furthermore, the algorithm elaborated from the graph visualisation algorithm provides good results with a low computational complexity. The maintenance of the algorithm is facilitated as the classifications made in the ontology contribute to simplify the algorithm. Using a ranking approach also allows the parallelization of updates, as the documents located on the same rank have no dependencies against each other.

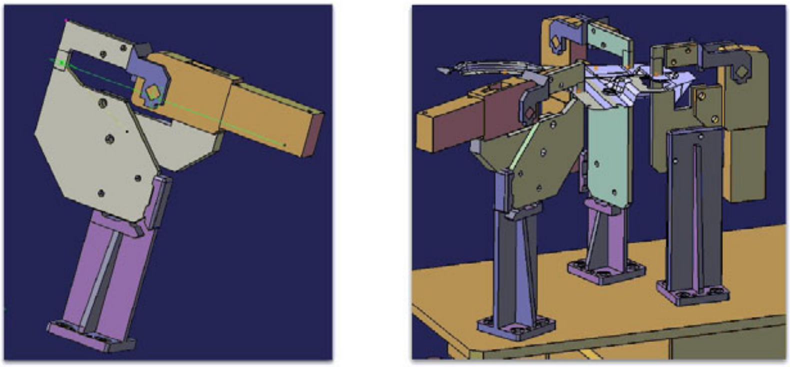
6 Scenario

This section presents the application of the proposed framework in a scenario, showing how it helps experts in template update related tasks.

6.1 Scenario Description

The scenario is articulated around a clamp template (figure 5 (a)) that aims at holding objects. It was designed with a CATIA V5 CAD system using the dedicated template workbench. This template is itself composed of four template instances. The clamp template is used in several assemblies. Figure 5 (b) shows an assembly context where three instances of the clamp template are present. They are used to hold a metal sheet in a manufacturing context. The clamp instances have different configurations, which are driven by individual parameter settings.

In this scenario an engineer is involved in the design of a new tooling station. He resorts to templates from a library to not design it from scratch. The tooling station requires handling metal sheets, so the engineer looks up in the library for a template providing this functionality and finds the clamp template. However, when looking into details, he realizes that the clamp is only meant to fasten horizontal surfaces.



(a) Clamp template (b) Clamp instances handling a metal sheet

Fig. 5. Three different instances of a clamp template in a metal sheet handling context

6.2 Issue Solving

The template user raises an issue that uses the decision support system (process (a) presented in figure 3). Four stakeholders are involved in the decision process: the template maintainer (A), the template user (B), a person in charge of the costs (C) and an electrical engineer (D). Figure 6 shows the argumentation that takes place to find a solution. Three positions are proposed for this issue, which are possible solutions for the problem. Each position refers to a rough sketch that illustrates the proposed ideas. Then, stakeholders provide their opinions on the positions according to their point of view. At this stage, two solutions fit the problem. To get more information on the initial issue, the template maintainer asks a question about the time constraint to deliver the new template version. In order to provide the new template in time, the chosen solution is to allow the modification of the angle of the clamp. So the desired angle can be set during the instantiation of the template.

The adopted solution is to modify the angle of the clamp template with an input parameter in order to be able to generate clamp instances with different angles. The resulting clamp will then be manufactured with a permanent angle. Now the planned modifications of the template have to be added and documented in the system. Then the template can be updated.

6.3 Template Update

The proposed process has been designed in order to interfere as less as possible with the existing company processes. The framework that extends the IBIS provides indications about the template to be modified and the planned updates. Here the planned modifications are to change the angle of the clamp by using an input parameter. The angle has to be provided by the "vertical blade", which is the central part of the clamp. However the "vertical blade" is a template instance, so the best solution would be to

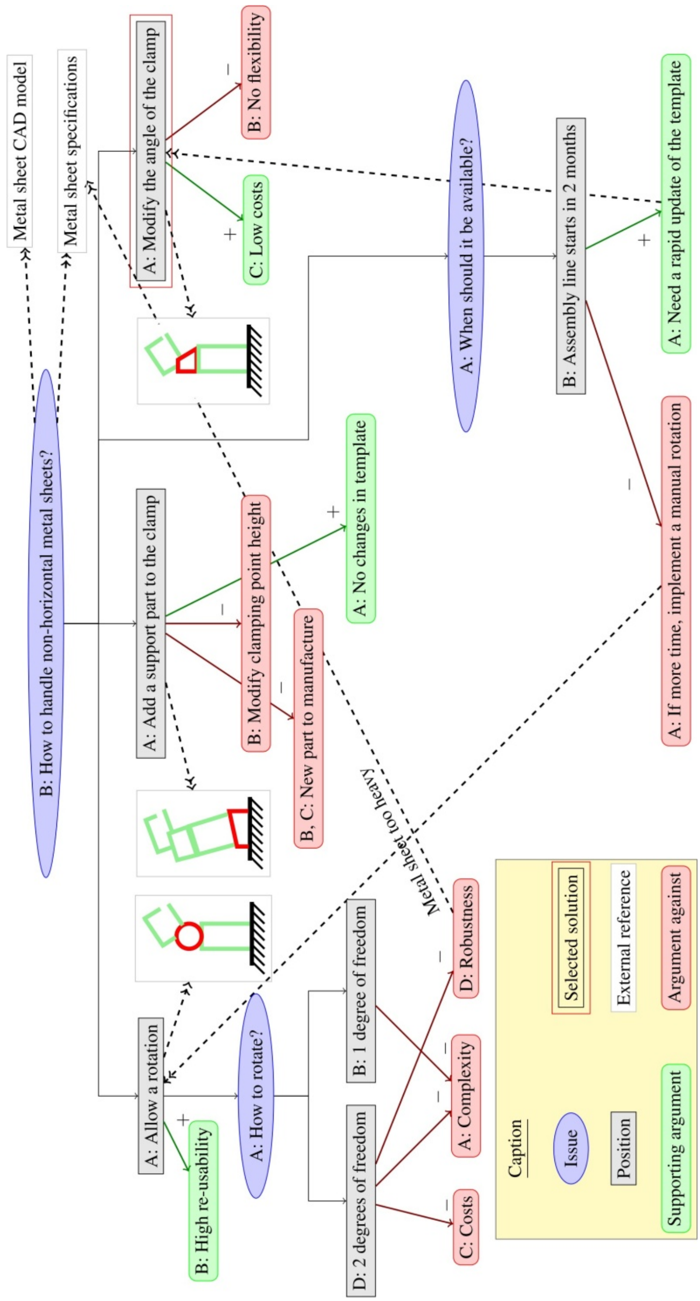


Fig. 6. Issue-based decision process: overview of the result

update its template definition by adding an angle parameter and corresponding rules that will drive the design of this template. Thus modifications are only applied to the "vertical blade" to point out the benefits of the update sequence on a specific case.

After the update, actual changes to the templates should be documented in the system. This includes the modified documents with a summary of the modifications. This summary should be explicit enough in order to allow persons in charge of the template instances updates to derive the necessary actions to update the existing template instances.

6.4 Models Analysis

In order to be able to take advantage of the definition of the domain in the ontology and to compute an update sequence, it is necessary to instantiate the concepts and properties from actual documents. This corresponds to the subprocess (b) of figure 3.

The first step is to extract relevant information from the models, such as the type and the contents of the documents, the relations, the template definition, etc. The analysis of documents is realised by a software developed in C++ and uses the CATIA V5 CAA API from Dassault Systèmes. This application analyses all CAD related documents, i.e., CATParts, CATProducts, catalogues, V4 models, etc. From the retrieved data, the OWL ontology is automatically instantiated, which now constitutes a knowledge base on the CAD related documents.

6.5 Update Sequence Generation

In the presented scenario, a single template document has been modified so far: the "vertical blade.CATPart" and will be the input of the algorithm. The corresponding computed sequence is shown in figure 7. The rectangles represent documents, the dashed line arrows point to the instances of a template and the full line arrows target a document contained in another. The figure shows that four ranks were created. The next section will explain how to use this sequence to help with the update of instances.

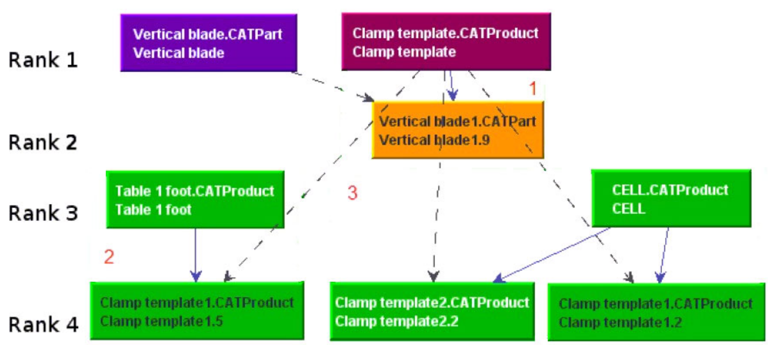


Fig. 7. Example of a computed update sequence

6.6 Instances Update

Figure 7 shows the 8 documents among a total of 92 that are concerned by the update process. The "vertical blade" is the updated template and has an instance located in the "clamp template". Through this relationship, the "clamp template" is automatically included in the update process at rank 1. The actions to undertake are first to load the "clamp template" document that will implicitly load the "vertical blade" instance. Now the engineer checks in the IBIS-based system what modifications were applied to the "vertical blade" template. Then the context, which is the clamp template, has to be updated to in order provide the new input parameter to the "vertical blade". Then at rank 2 the old "vertical blade" instance is replaced. This results in a modification of the "clamp template" template, which also has to be propagated to its instances that are located in the "table 1 foot" and the "CELL" products. This is addressed by rank 3 and 4.

7 Outlook

This paper addresses the update of KBE templates and focuses on the update issues solving and the corresponding resolution process, as well as on the application of the modifications to the instances. A framework is proposed that provides a methodology and tools to enhance the process of template update, from the cause of the update (bug fix, new requirement, improvement, etc.) to the propagation of the changes to the instances of the template. It is composed of two main systems: a decision support and design rationale system as well as a template instances update support system.

The proposed framework presents various benefits. First, it helps to solve template issues through collaboration and provides a way to document the evolution of the templates. Regarding the update of instances, the framework generates a sequence of necessary updates from knowledge present in the ontology and thus saves time by avoiding the analysis of the assemblies in order to evaluate the impacts of the changes implemented in the template. Furthermore, the sequence is based on ranks which allow parallelising update tasks. The designed ontology can be easily reused for other applications such as the visualisation of dependencies between documents at a large scale. The separation between the knowledge and the algorithm facilitates the maintenance as well as the evolution of the system. The coupling with another CAD system is easier as it consists in an evolution of the ontology with few modifications.

Further work would include the enhancement of the system by automating the last step of the process: the instances updates. Another possibility would be to extend the decision support system with case-based reasoning in order to ruse past experiences for new problems. Finally the validation of the scalability of our approach on large assembly sets as well as the visualisation of large graphs remain as further objectives.

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