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A BOTTOM-UP APPROACH FOR AUTOMATED SYNTHESIS SUPPORT IN THE ENGINEERING DESIGN PROCESS: PROTOTYPES

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1. Introduction

Developments in the modern world lead to ever-increasing pressure on the industrial engineering design process. Companies compete to deliver products to the market at a higher pace than ever before, putting stress on the design process itself as deadlines move closer and closer, but quality demands remain.
In the engineering design process without computer support, the amount of knowledge and experience of the engineers determine the design speed and ultimately the quality of the solution. The currently available CAD support focuses mainly on analysis and optimization, leaving the critical process of finding a solution proposal to human designers.
The paper presents prototypes of a new type of CAD tool which automatically generate, evaluate and improve multiple solutions. It allows the designer to explore a detailed solution space, providing insight in the possibilities and constraints of a design. The information available in the solution space is identical with the level of detail of existing analysis methods such as well-known engineering formulas, computer simulations and finite element analysis. This makes it especially suitable for use in industrial environments, since it directly incorporates the levels of abstraction and available engineering knowledge.
Previous research yielded a number of prototypes that are well-defined in functionality and each with a specific domain. They are used in this paper to illustrate several key features of automated synthesis support.
First, the engineering design process with currently available CAD support is discussed in more detail. Next, the general methodology of automated synthesis support is presented followed by several prototypes to demonstrate typical features. Finally, conclusions as well as several future research topics are given.
This paper shows the feasibility of a bottom-up approach to successfully develop design tools.

2. CAD in the engineering design process

The design process with current CAD support is presented in figure 1a. The role of CAD is focused on analysis and parameter optimization, leaving the critical process of solution generation to the human designers [Ullman 2002]. A part of this solution generation process is synthesis: the activity where reasoning takes place from statements on function (or intended behavior) towards a description of form [Chakrabarti 2002].
The design process is modeled to identify the different steps and position the available CAD support. The engineering design process begins when the engineer gathers the requirements for the problem he

has to solve. From this information, he/she starts a synthesis process (a): how to solve the problem. This leads to one or more solution proposals (b) which are expected to meet the required performance. For each proposal, an analysis (c) is executed to determine the performance. This is followed by evaluation (d) of the results. Here, the engineer has three choices: proceed with this proposed solution for further optimization (e), generate an entirely different proposal (f) or to stop the design process when he found an acceptable solution (g).

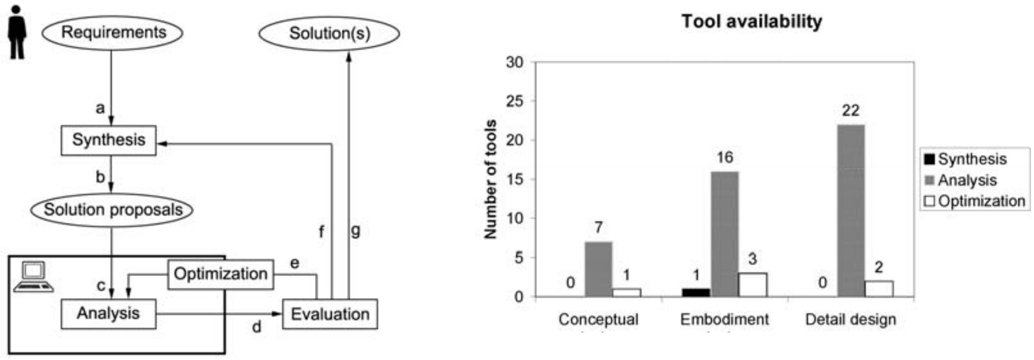

Figure 1. a) Current CAD support, b) Tool availability

An internet survey has been conducted to determine the amount of CAD tools which are available during a specific design process, in this case the design of composite structures. The engineering process is divided into phases according to Pahl and Beitz [Pahl Beitz 1996]. The conceptual phase handles the layout of the structure. The embodiment phase handles the material choice, the number of layers and their thickness. The orientations of the individual plies, as well as the construction details are specified in the detail phase.

The survey revealed that approximately 22 tools are available for this domain, according to Tragter [Tragter 2002]. They are divided among the different phases as shown in figure 1b, showing that all tools offer analysis support in the detail design phase. Analysis support is present in all phases, although significantly less so in the conceptual phase compared to the detailing phase. During embodiment design, 3 tools offer optimization support and one assists with synthesis, however with very limited functionality.

CAD offers very little assistance during the creation of the proposed solutions, which still depends heavily on the skill of the engineer. The same occurs when, after analysis, the proposed solution is adjusted to better meet the requirements. It is nearly impossible for engineers to find optimal solutions due to the size of the solution space and the amount of design freedom. Consequently, only a limited amount of alternatives is studied after executing long trial and error loops to find an acceptable solution.

These observations are in accordance with research done by Ullman [Ullman 2002] and Simpson et al. [Simpson 2001].

3. Synthesis based engineering support

Identifying the above mentioned problems, a new tool concept is proposed where the role of the computer is significantly increased. It also includes the generation of solution proposals and its evaluation and improvement process. The algorithms are based on a combination of knowledge rules, both well-known engineering formulas and rules of thumb, and search routines. The tool presents multiple feasible solutions based on specifications of a single problem. Not unlike the methods presented by Campbell et al. [Campbell 2003] using agent based systems.

The bottom-up approach presented in this paper focuses on specific, well-defined engineering domains. These engineering tasks are found in the configuration/redesign process for customer specification, a reaction on the increasing pressure on industrial companies. Changes are made to an

existing and proven concept so the product structure and the design steps remain intact. Analysis methods are well known within this (company specific) configuration process and are directly integrated in the tool to determine the performance of each proposed solution.
The types of engineering problems which are handled can be classified as problems with complete description and environment but incomplete specification, using emergent synthesis terms [Ueda 2001].
The engineer is able to insert the problem specifications and/or solution requirements and receives a large number of valid solutions, arranged by quality. Looking at the solutions, he/she can judge and adjust the specifications to steer the design process to the optimal situation.

4. Automated synthesis support tools: prototypes

Several features of the automated synthesis support tools are presented here using previously developed prototypes. Larger screenshots of the prototype tools can be found on the website [Website OPM 2005].

4.1 The spring designer

The synthesis tool for the design of compression springs is used to illustrate the capability of solving under defined engineering problems. The parameters the engineer has to determine are the degrees of freedom of the design. He/she has to choose values for all unknowns in order to use analysis methods to check the quality of his design. The fact that he has to choose all parameters before analyzing the solution forces him to make choices of which he cannot always see the consequences [Ullman 2002]. This is caused by the analysis formulas, which only work for fully defined systems. Using a spring as an example, this is illustrated in figure 2a.
In this figure, the analysis and synthesis procedure of a spring are shown, in accordance with definitions used by Chakrabarti [Chakrabarti 2002]. Using well-known analysis formulas, an engineer can only calculate the properties (function) of a compression spring (form) when all parameters are known. However, an engineer that requires a specific stiffness (a functional requirement) has to begin a trial-and-error loop to search for a solution that meets the requirement.
A prototype has been developed for the synthesis based spring designer, shown in figure 2b. The tool generates a complete range of feasible springs (solutions), based on an incomplete set of requirements. Even if only the required stiffness is entered in the tool, solutions are generated.

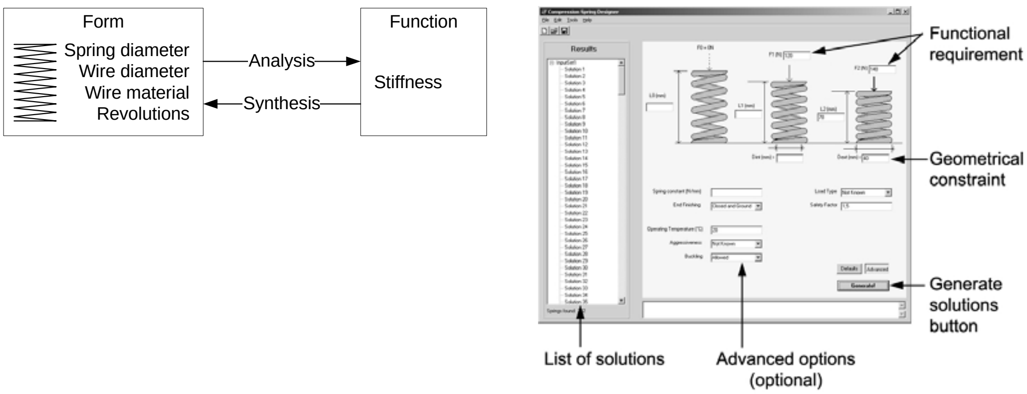

Figure 2. a) Analysis and synthesis, b) The spring designer

Each solution is a fully defined spring, meeting the engineering requirements. The tool uses standardized wire diameters to create a finite amount of solutions. Extra checks like buckling or corrosion resistance can be made, using the 'advanced options'. The results can be presented to the engineer in order of minimum costs, weight, length, etc.
For this specific prototype, knowledge of the manufacturing process is used as synthesis rules. These 'rules of thumb' are experience-based knowledge of the company and strongly related to the available

production machines. Using these relations, calculation effort can be significantly eased [Draijer 2002]. Elicitation of these rules is relatively straightforward because of the well-defined engineering domain and manufacturing processes of the subject.

4.2 WATT: Synthesis of mechanisms

The tool for automated synthesis of bar mechanisms is used to illustrate the increased availability of specialized engineering knowledge resulting from a synthesis tool. The commercially available tool, called WATT, as well as a demo version can be found online; www.heron-technologies.com.
An engineering problem which calls for a solution in the form of a bar mechanism can be the request to transfer products over a specific trajectory, illustrated in figure 3a. The conveyor belts and product are sketched to show a situation where this problem could occur. A mechanism can be designed to describe the required trajectory resulting in a reliable and cheap solution.
The engineer knows what product path he/she requires and the question is: what available solutions are there and which mechanism is the most favorable?
The required solution specifications are entered into the synthesis tool, shown in figure 3b. The geometric constraints are areas where the mechanism can be attached to the ground.
The program has knowledge of common mechanism types and the matching analysis methods. Although a limited number of mechanism types exist, it is possible to create numerous solutions with them. Based on the required specifications and constraints, a list of feasible solution proposals is generated within seconds. Using a qualitative ranking, based on the minimum path deviation, the most accurate proposals are located at the top of the list.
Through a visual representation and qualification of the generated mechanisms, the engineer is able to scan the available options, picking out the best solution for his scenario.

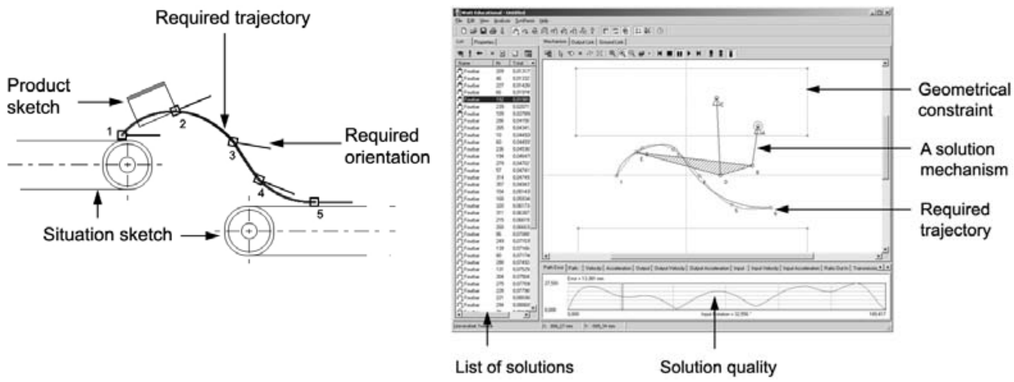

Figure 3. a) Problem sketch, b) WATT

The design of this type of mechanism is a complicated and specialized field of engineering. Using the synthesis based engineering tool, the process of designing a linkage mechanism now becomes available for many engineers, which results in increased accessibility to specialized knowledge, although a certain experience influence is likely to remain.
Increasing the accessibility of specialized knowledge is also done by Schotborgh et al. [Schotborgh 2005] for the design of flexure hinges, a specialized field of engineering. Methods are derived to determine the geometry of a flexure, based on the functional requirements. This strongly reduces the amount of costly trial and error iterations in finite element analysis tools.

4.3 The composite designer

A synthesis tool is developed which generates optimal composite structures, based on mechanical load scenarios. The representation of the solution space has been the focus point of this prototype.

Composite structures are combinations of two or more different materials. In this case, unidirectional layers of mechanically resistant fibers bonded by a matrix material, for use in airplane wings, amongst others, are shown in figure 4a.
The materials of the fiber and the matrix, together with the number of layers and relative orientations, are the degrees of freedom of the engineer. The known problem specification is in this case the load case of the complete sheet. The solutions which the tool generates are formed by a combination of different materials in their optimal orientation, taking manufacturing limitations into account.
After the synthesis tool produces many feasible designs, these solutions are presented to the user in a clear and structured manner so the engineer can interpret the solution space. It is of vital importance that the engineer gains insight in the differences between the presented solutions. He can than select the solution that suits him best.
Often there is more than one aspect of importance, for example: mechanical performance, safety factors, cost and manufacturability. A particular solution can have the highest score in one aspect, but perform poorly in another. With many aspects to judge, the engineer can use some assistance.
Representing the solution space is done by plotting graphs where qualitative aspects can be plotted against any other, shown in figure 4b. In the graph, each square represents a laminate design. This allows visual evaluation of its relative score for each aspect. The x-axis shows the global performance: a weighted combination of cost, weight and mechanical performance.

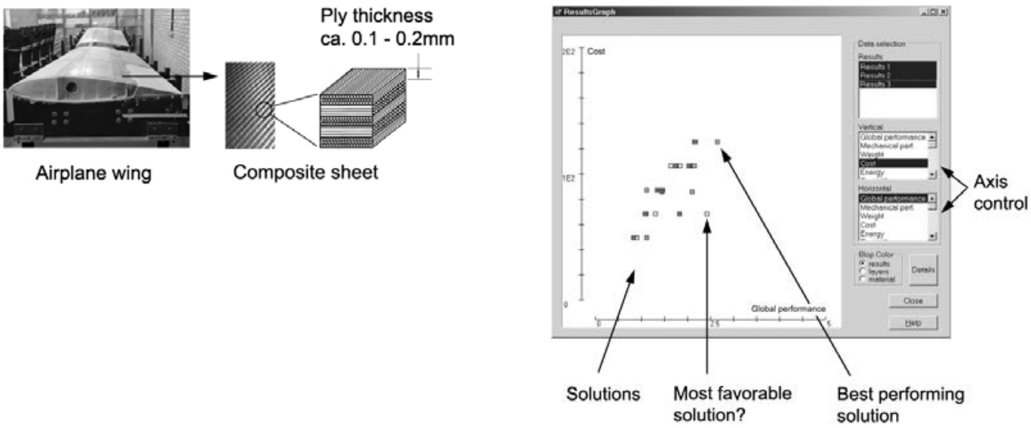

Figure 4. a) Composite sheet, b) The composite designer

As seen in the figure, the solution with the best global performance can be found easily. However, comparing this with the cost aspect reveals a second candidate for the most favorable solution since it approximates the performance of the best solution, for nearly half the price.

4.4 Remaining prototypes

Two other prototypes have been developed focusing on multi domain integration and dynamic mechanism design. They are presented briefly.
The spindle drive designer focuses on multi domain integration, figure 5a. A spindle drive is a linear positioning mechanism frequently used in accurate assembly machines, for instance electronic component placing on printed circuit boards. The system consists of an electromotor driving a spindle through a set of gears. A carriage with a manipulator is mounted on the spindle, which is being accurately positioned using feedback control. In electro-mechanical problems, assembly of optimal partial solutions does usually not lead to an overall optimum. A schematic representation is given in the user interface presented in figure 5a.
The tool generates complete spindle drive systems, based on the functional requirements: in this case range of motion, positioning error and mass of the carriage. A detailed motion profile can also be entered. Catalogue components are used for the motor and spindle, since these are likely to be bought externally.

The properties of the different solutions are presented using analysis techniques in the domains of dynamics (Bode diagram), electrical engineering (motor characteristics) and control systems (Root locus plot) can be selected by a drop down menu. The designer can view the different aspects of one solution, or look at the same aspect of different solutions for comparison.
Another prototype handles the design of a dynamic mechanism, figure 5b. The user interface gives three representations of the mechanism. In this design process, it is of importance to find an (optimal) balance between stiffness and weight in order to design a system with good dynamic behavior. The synthesis tool presented here can be used for cam driven mechanisms. It generates the optimum geometry of the mechanism components and cam profiles from dynamic point of view.
The figure shows an example of a mechanism. A cam is driven by a motor, which in turn drives a mechanism, aimed at positioning the output element. The configuration of the mechanism topology is entered in the system by the designer (in this case a cam, lever, rod and a lever). The geometrical properties of all the components between the motor and the output element are of great importance for the dynamic behavior of such systems.

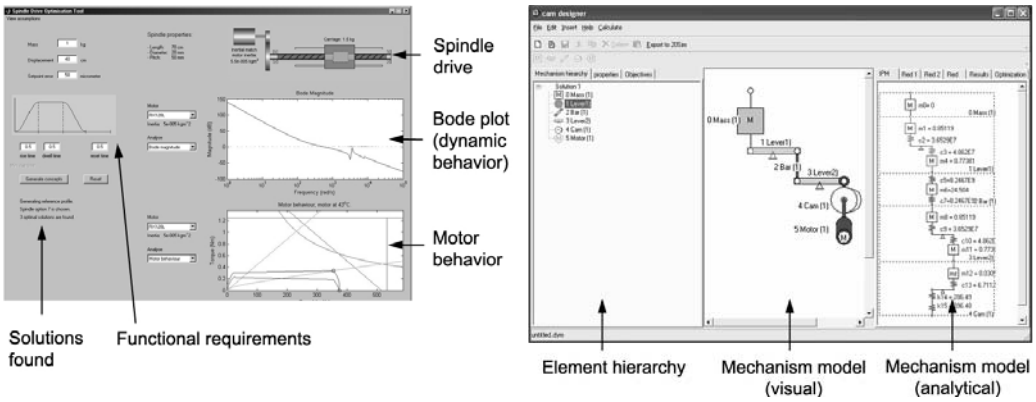

Figure 5. a) Spindle drive designer, b) The mechanism optimizer

The tool lets the engineer specify the elements of the mechanism, after which the geometry and the cam profile is optimized for dynamic behavior. Constraints can be added, for instance the length of a bar that is to remain unchanged.

5. Conclusions

A number of conclusions can be drawn from the prototypes. These conclusions also concern the general methodology that is distilled from the tools.

- The methodology is applicable for a wide range of engineering domains: from basic construction elements to dynamic mechanisms, electro-mechanical systems and specialized fields of engineering like composite design and flexure elements.
- The engineering process is speeded up substantially. Designing a mechanism takes minutes and an optimal spring is found in seconds. This will be quantified more accurately in future research using industrial cases.
- The engineer is provided with a wide range of detailed solutions, based on under defined specifications. All missing parameters are determined.
- The engineer explores the solution space by examining a visual representation of the relative qualities of the solutions, giving insight in alternatives and limitations.
- Expert knowledge becomes accessible for less experienced engineers.

Development of automated synthesis support tools is possible in all domains where knowledge rules are available, and combinations thereof such as electro-mechanical systems.

A limitation of the presented approach is the fact that a new tool has to be developed for each new engineering topic. The information content of this topic has to be well-defined and finite in order to deliver a tool with clear functionality.

Due to the well-defined nature of tool, it can form the basis of a bottom-up development of knowledge based expert systems such as those presented by Campbell [Campbell 2003] and Yoshioka [Yoshioka 2004].

Further research is required to increase the efficiency and application area of tool development. The next section presents several future research topics.

6. Future research

After presentation of the achievements of previous research, future research topics are discussed in order of priority. To keep close attention to the need of the industry, it is of importance to work in close cooperation with companies. Use of a case problem and developing a tool prototype for specific industrial situations, while focusing on research subjects, delivers the proof of principle.

6.1 Engineering knowledge (started 01-05-2005)

The synthesis and evaluation algorithms should converge towards feasible solutions as efficiently as possible. The required engineering knowledge is available in the company, since it designs feasible solutions as well. Knowledge can consist of explicit rules, rules of thumb and/or experience. Research will focus on methods to extract these knowledge rules and the translation into algorithms.

6.2 Multi domain integration (started 01-01-2006)

Since this is a bottom-up method, attention is needed to be able to support the design process on a higher level. Multiple synthesis tools, possibly from different domains, are integrated to perform synthesis over multiple domains. The framework and communication protocols, being hierarchical and/or cooperative, are being developed.

6.3 Large parameter spaces (started 01-01-2006)

When engineering problems become more complex, in both number of degrees of freedom, as well as the use of more extensive analysis techniques, special mathematical attention is required. Especially automatic navigation and optimization in this vast solution space should be supported by well tuned mathematical techniques.

6.4 General toolbox

The above mentioned research topics are likely to result in general methods and procedures, together with algorithms and software codes. These building blocks will be stored in a toolbox to allow efficient development of synthesis applications.

6.5 Expanding towards customers

Having an automated synthesis tool available in the marketing department can greatly decrease the response time in customer interactions. Solutions can be shown to the customer immediately and, if a cost calculation module is integrated in the tool, a price indication can be given. The customer can visit an internet site and see directly if and how his problem can be solved, find out how much is costs and what the delivery time would be.

6.6 Expanding towards production

Automating the design of a product or a part is an important step, but the production of this part still needs preparation time. If the design process of a product/part is automated, the planning and preparation for manufacturing can be automated next to further decrease the customer response time.

References

Campbell, I.C., Cagan, J., Kotovsky, K., 2003, "The A-Design approach to managing automated design synthesis", Res Eng Design 14: 12-24, Springer-Verlag

Chakrabarti, A., 2002, "Engineering design synthesis", Springer-Verlag London

Pahl, G., Beitz, W., 1996, "Engineering Design: A systematic approach", ISBN3540199179, Springer-Verlag London Ltd.

Draijer, H., Kokkeler, F.G.M., 2002, "Heron's synthesis engine applied to linkage design; the philosophy of WATT software", Proceedings of DETC'02, ASME 2002 Design Engineering Technical Conferences and Computer and Information in Engineering Conference, Montreal

Schotborgh, W.O., Kokkeler, F.G.M., Tragter, H., van Houten, F.J.A.M., 2005, "Design graphs for flexure elements and a comparison between three types", Journal of Precision Engineering, Elsevier Science Ltd.

Simpson, T.W., Peplinksi, J.D., Koch, P.N., Allen, J.K., 2001, "Metamodels for Computer-based Engineering Design: survey and recommendations", Engineering with Computers, Springer-Verlag London Ltd.

Tragter, H., 2002, "The Composite Designer", master thesis CTW.02/TMK-5284, University of Twente

Ueda, K, 2001, "Synthesis and emergence – research overview", Artificial intelligence in engineering 15: 321-327, Elsevier Science Ltd.

Ullman, D.G., 2002, "Toward the ideal mechanical engineering design support system", Res Eng Design, vol. 13: pp. 5-64, Springer-Verlag

Website OPM, 2005, University of Twente, Faculty of Engineering Technology, department of design, production and management ; research ; design engineering,
www.opm.ctw.utwente.nl/research/design_engineering/

Yoshioka, M., Umeda, Y., Takeda, H., Shimomura, Y., Nomaguchi, Y., Tomiyama, T., 2004, "Physical concept ontology for the knowledge intensive engineering framework", advanced engineering informatics, Elsevier Science Ltd.

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