Towards a Generic Model of Smart Synthesis Tools

W. O. Schotborgh[1], H. Tragter[1], F. G. M. Kokkeler[1], F. J. A. M. van Houten[1], T. Tomiyama[2]

[1] Laboratory of Design, Production and Management, Department of Mechanical Engineering, Faculty of Engineering Technology, University of Twente, Enschede, the Netherlands
[2] Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Delft, the Netherlands

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

Keywords
Computer Aided Design, Synthesis, Design Process Model

1 Introduction

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

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

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

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

2 CAD Development

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

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

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

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

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

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

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

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

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

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

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

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

3 Smart Synthesis Project

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

3.1 Vision and Mission

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

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

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

3.2 Strategy

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

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

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

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

3.3 Design Process

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

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

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

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

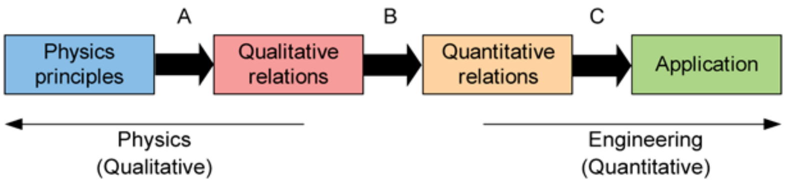

Fig. 1: Knowledge development

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

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

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

4 Research Topics

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

4.1 Design Knowledge

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

4.2 Problem Structuring

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

4.3 Large Solution Spaces

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

4.4 Multi-Domain Integration

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

5 Conclusion

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

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

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

6 Acknowledgement

The authors gratefully acknowledge the support of the Dutch Innovation Oriented Research Program ‘Integrated Product Creation and Realization (IOP-IPCR)’ of the Dutch Ministry of Economic Affairs.

References

1 Brown D, Waldron MB, Yoshikawa H (1992) Intelligent Computer Aided Design, IFIP Transactions B-4, North-Holland, Amsterdam

2 Cagan J, Campbell M I, Finger S, Tomiyama T (2005) Framework for Computational Design Synthesis: Model and Applications, Journal of Computing and Information Science in Engineering, ASME

3 Campbell IC, Cagan J, Kotovsky K (2003) The A-Design approach to managing automated design synthesis, Res Eng Design 14:12–24, Springer-Verlag

4 Draijer H, Kokkeler FGM (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 2002, Montreal

5 Gero JS (1985) Knowledge Engineering in Computer-Aided Design, North-Holland, Amsterdam

6 Ishii M, Tomiyama T, Yoshikawa H (1994) A Synthetic Reasoning Method for Conceptual Design, in Wozny MJ and Olling G (1994) Towards World Class Manufacturing, IFIP Transactions B-17, North-Holland, Amsterdam, pp 3–16

7 Kiriyama T, Tomiyama T, Yoshikawa H (1992) Qualitative Reasoning in Conceptual Design with Physical Features, in: Faltings B, Struss P (1992) Recent Advances in Qualitative Physics, The MIT Press, Cambridge, MA, USA, pp 375–386

8 Kurtoglu T, Campbell MI (2006) A graph grammar based framework for automated concept generation, Proceedings of the International Design Conference Design 2006, pp 61–68, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb

9 Kurumatani K, Tomiyama T, Yoshikawa H (1990) Qualitative Representation of Machine Behaviors for Intelligent CAD Systems, Journal of Mechanism

and Machine Theory, Special Issue on Computational Theories of Design – Applications to the Design of Machines, vol 25, issue 3, pp 325–334
10 Maimon O, Braha D (1996) On the complexity of the design synthesis problem, IEEE transactions on systems, man, and cybernetcis – Part A: Systems and humands, vol. 26, issue 1, January 1996, IEEE
11 Minderhoud S, Fraser P (2005) Shifting paradigms of product development in fast and dynamic markets, Reliability Engineering & System Safety, 88(2): 127–135
12 Schotborgh WO, Tragter H, Kokkeler FMG, van Houten FJAM (2006) A bottom-up approach for automated synthesis support in the engineering design process: prototypes, proceedings of Design 2006 9th international design conference, pp 349–356
13 ten Hagen PJW, Tomiyama T (1987) Intelligent CAD Systems I: Theoretical and Methodological Aspects, Springer-Verlag, Berlin
14 Weld D, de Kleer J (1987) Readings in qualitative physics, Morgan Kauffman
15 Zhang WY, Tor SB, Britton GA (2001) A prototype Knowledge-Based System for Conceptual Synthesis of the Design Process, Int J Adv Manuf Technol 17: 549-557, Springer-Verlag London