Template Based Design Analysis

– An Alternative Approach for the Engineering Designer to Perform Computer-Based Design Analysis.

HÅKAN PETERSSON | DEPARTMENT OF DESIGN SCIENCES
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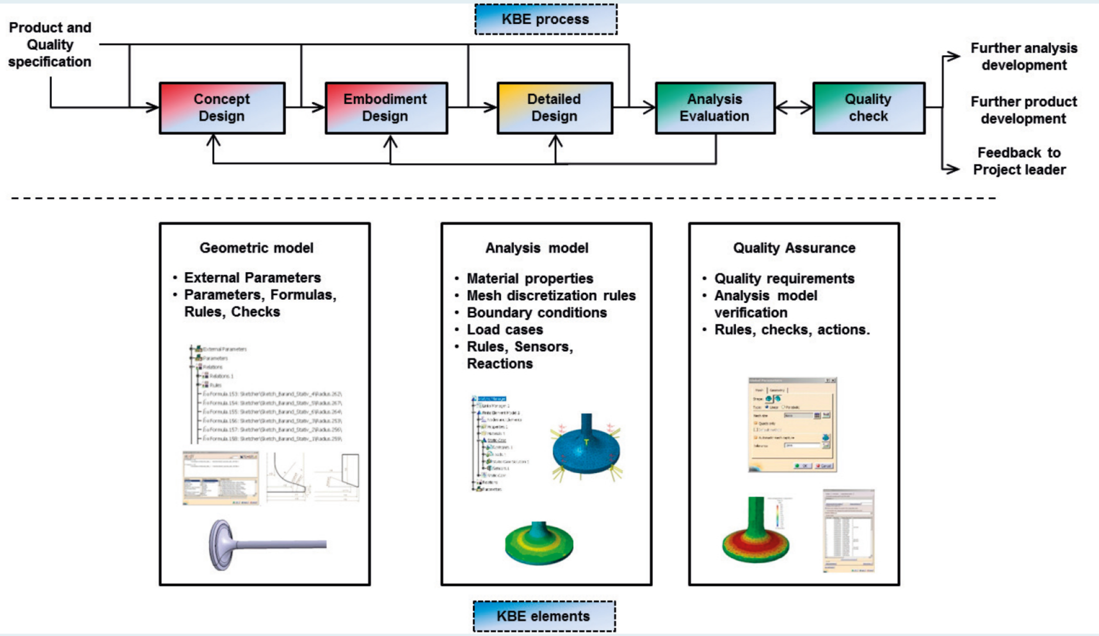

DOCTORAL THESIS

Template-Based Design Analysis

– An Alternative Approach for the Engineering Designer to Perform Computer-Based Design Analysis

Håkan Petersson

LUND
UNIVERSITY

DOCTORAL DISSERTATION

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Abstract

The current trend in industry to encourage engineering designers to take an active part in the analysis of their own design solutions is apparent in many companies today, domestically as well as abroad.

From a research project with the objective to develop a computer-based design system for the design of lightweight grippers, one of the major difficulties was to overcome the system users' lack of knowledge and experience in the design of lightweight structures and Computer-Based Design Analysis (CBDA). CBDA here refers to the use of analysis tools such as Finite Element Analysis (FEA) and computer-based structural optimization. In order to handle these difficulties, the author introduced the use of *templates.* In the given context, a template refers to an especially pre-formatted code, which contains the implemented information/knowledge necessary to perform a specific task on an operational level. It should be noted that the use of templates as a means of support in performing a specific design or analysis task is not a new phenomenon in industrial practice. Inspired by the opportunities provided by the template approach, the *main objective* set out for the thesis project was to *facilitate the active participation of the engineering designers in performing CBDA singlehandedly, or in any other organizational setting, by utilizing a Template-Based Design Analysis (TBDA) approach, as an integrated part of their activities within the engineering design process.*

The evolutionary research approach for the development of the TBDA approach is based on surveys in Swedish as well as international industry, literature surveys, the development of a Generic Design Analysis (GDA) process model (facilitating integration of the activities between CBDA and engineering design) and a number of demonstrator projects to deepen the insights into TBDA. Note that as the TBDA approach is intended for use in industrial practice, the approach is independent of specific engineering design and product development processes utilized in industry.

The conclusion of the thesis work clearly supports the claim that *TBDA is not only a competitive approach to current alternatives in supporting the engineering designers performing CBDA, but also of a complementary nature providing functionality not included in the alternative approaches currently used in industrial practice.*

Key words: Computer-Based Design Analysis, Engineering Design process, Template, and Template-Based Design Analysis.

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To My family

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My main advisor, Professor Robert Bjärnemo, although he often ran out of time, was always there for me guiding me through the process with his encouragement, support and willingness to discuss my research topic and engineering design in general. It would have been much more difficult for me to complete this thesis without Robert's outstanding ability to keep me on track or without the fruitful discussions he inspired during the work.

My thanks also go to Dr. Damien Motte for his support in the writing of conference and journal publications as well as this PhD thesis; his ability to structure and edit conference papers has been most valuable as has his accuracy and ability as a helping hand. I also want to thank Dr. Martin Eriksson, expert design analyst at Validus Engineering, Sweden, and former PhD student at the Division of Machine Design, for his help in evaluating gripper concepts and for allowing me to join into his own research project. I am also in debt for his expert help when writing some of the papers. I also want to send my gratitude to the rest of the staff at the Division of Machine Design. Even though they are busy, they readily took the time to talk and discuss scientific problems in general. My colleagues at Halmstad University may not always understood why I did it, but when I wanted to discuss problems, they listened and supported me.

Finally, I want to thank my wife Anna and my daughter Ellinor for their understanding and patience when I had to work late nights and weekends to be able to complete this PhD thesis. They also helped and supported me during my many, not so lonely trips to conferences around the world.

Lund, April 2016

Håkan Petersson

Populärvetenskaplig sammanfattning

Vid framtagning av nya produkter måste man utgå ifrån de behov som den blivande kunden ställer i form av krav och önskemål på produkten för att den ska vara intressant att inhandla och använda. För att säkerställa att den blivande produkten har de egenskaper som efterfrågas, används idag omfattande simuleringar av den blivande produktens egenskaper. Simuleringar består i avancerade beräkningar med hjälp av dator. Genom att utföra dessa tidigt i utvecklingsarbetet, så kan man väsentligen korta ned tiden för utveckling och konstruktion av produkten. Detta uppnås framför allt genom att minska behovet av att bygga och prova prototyper. Beräkningar i utvecklings- och konstruktionsarbetet spelar därför idag en väsentlig roll för att ta fram konkurrenskraftiga produkter på ett snabbt och effektivt sätt.

I denna avhandling har ett nytt tillvägagångssätt tagits fram för att låta konstruktörer själva beräkna sina konstruktionsförslag. Hittills har merparten av alla beräkningar av detta slag genomförts av beräkningsingenjörer. Nu kan man genom att tillämpa den i avhandlingen framtagna tillvägagångssättet att med hjälp av digitala mallar (program för att lösa speciella uppgifter i konstruktionsarbetet) och det föreslagna tillvägagångssättet MallBaserad KonstruktionsAnalys (MBKA) tillåta att konstruktörer, som vanligtvis inte är specialister på beräkningar, självständigt kan utföra sådana analyser. Mallarnas roll är alltså att överbrygga brister i kompetens och erfarenheter av konstruktionsberäkningar.

Redan idag finns konkurrerande sätt att tillåta konstruktörer att delta i beräkningsarbetet, men då oftast med direkt stöd av en beräkningsingenjör och med tillgång till riktlinjer. Dessa kräver att konstruktören har en viss grundkompetens för att kunna följa och tillämpa dessa. MBKA ställer inte dessa krav på kompetens och insikter, vilket gör att den kan betraktas inte bara som en konkurrent till existerande tillvägagångssätt utan också erbjuda ett helt unikt och nytt stöd genom att inte kräva kunskaper och insikter om konstruktionsberäkningar.

Av de reaktioner som erhållits i intervjuer i svensk industri, så ter sig framtiden för MBKA som mycket lovande. Många företag funderar redan idag på att införa tillvägagångssättet. Innan så kan ske, måste dock MBKA utvecklas ytterligare, vilket är målet för den fortsatta forskningen.

Nyckelord: Datorbaserad konstruktionsanalys, Konstruktionsprocess, undersökning, beräkningsstöd samt minskade ledtider, MallBaserad KonstruktionsAnalys.

Abstract

The current trend in industry to encourage engineering designers to take an active part in the analysis of their own design solutions is apparent in many companies today, domestically as well as abroad.

From a research project with the objective to develop a computer-based design system for the design of lightweight grippers, one of the major difficulties was to overcome the system users' lack of knowledge and experience in the design of lightweight structures and Computer-Based Design Analysis (CBDA). CBDA here refers to the use of analysis tools such as Finite Element Analysis (FEA) and computer-based structural optimization. In order to handle these difficulties, the author introduced the use of *templates.* In the given context, a template refers to an especially pre-formatted code, which contains the implemented information/knowledge necessary to perform a specific task on an operational level. It should be noted that the use of templates as a means of support in performing a specific design or analysis task is not a new phenomenon in industrial practice. Inspired by the opportunities provided by the template approach, the *main objective* set out for the thesis project was to *facilitate the active participation of the engineering designers in performing CBDA singlehandedly, or in any other organizational setting, by utilizing a Template-Based Design Analysis (TBDA) approach, as an integrated part of their activities within the engineering design process.*

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Keywords: Computer-Based Design Analysis, Engineering Design process, Template, and Template-Based Design Analysis.

Appended papers

This thesis includes the following appended papers:

Paper I
Eriksson, M., Petersson, H., Bjärnemo, R., & Motte, D. (2014). *Interaction between computer-based design analysis activities and the engineering design process - An industrial survey*. *International Design Conference - Design 2014*, Dubrovnik, Croatia, May 19-22, 2014.

Håkan Petersson, Robert Bjärnemo, and Martin Eriksson have jointly established the survey questions to the companies, chosen the companies to be included in the industrial survey and performed the interviews. All authors have contributed jointly to the literature review. Martin Eriksson is the person mainly responsible for the paper structure. Håkan Petersson presented the paper at the conference.

Paper II
Motte, D., Eriksson, M., Petersson, H., & Bjärnemo, R. (2014). *Integration of the computer-based design analysis activity in the engineering design process – A literature survey*. *10th International Symposium on Tools and Methods of Competitive Engineering - TMCE'14*, Budapest, Hungary, May 20-24, 2014.

Håkan Petersson, Damien Motte, Martin Eriksson and Robert Bjärnemo have contributed jointly to the literature survey. Damien Motte has structured and presented the paper at the conference.

Paper III
Petersson, H., Motte, D., Bjärnemo, R., & Eriksson, M. (2015). *The engineering designer in the role of a design analyst - An industrial survey*, *NAFEMS World Congress 2015*. San Diego, CA, June 21-24, 2015

Håkan Petersson, Damien Motte, and Robert Bjärnemo have jointly developed and reviewed the question for the survey. Håkan Petersson is responsible for the implementation of the on-line survey and is responsible for targeting the respondents. All authors have reviewed the publication. Håkan Petersson presented the paper at the conference.

Paper IV
Eriksson, M., Bjärnemo, R., Petersson, H., & Motte, D. (2015). *A process model for enhanced integration between computer-based design analysis and engineering design*. To be re-submitted to the *Journal of Engineering Design*.

Martin Eriksson is responsible for the development of the Generic Design Analysis (GDA) process model presented in the publication. Robert Bjärnemo has contributed to the aspects of integration from an engineering design perspective and Martin Eriksson from a design analysis perspective as discussed in the publication. Håkan Petersson contributed to the section on method development activities. Damien Motte and Håkan Petersson reviewed the publication.

Paper V
Motte, D., Petersson, H., Eriksson, M., & Bjärnemo, R. (2016). *Development of a computer-aided fixture design system for lightweight grippers in the automotive industry*. Under revision by the *International Journal of Design Engineering*.

Håkan Petersson is responsible for the development of the design system presented. Damien Motte has made a substantial contribution to the background literature research on fixtures and fixture design process models and assisted in the structuring of the paper. Martin Eriksson has supported the main author regarding the design analyses, established material properties, generated concept candidates and assisted in the concept evaluation process and materials and concept evaluation. Martin Eriksson and Robert Bjärnemo have reviewed the publication.

Paper VI
Petersson, H., Motte, D., & Bjärnemo, R. (2013). *Integration of computer aided design analysis in the engineering design process for use by engineering designers*, *International Mechanical Engineering Congress & Exposition - IMECE2013*, San Diego, CA, November 15-21, 2013.

Håkan Petersson is responsible for the development of the solution presented. Håkan Petersson and Damien Motte have contributed jointly to the literature review. Damien Motte and Robert Bjärnemo have reviewed the publication. Håkan Petersson presented the paper at the conference.

Paper VII
Petersson, H., Motte, D., & Bjärnemo, R. (2015). *Using templates to support the engineering designer performing computer-based design analysis*, *International Mechanical Engineering Congress & Exposition - IMECE2015*, Houston, TX, November 13-19, 2015.

Håkan Petersson is responsible for the solutions of the template based design analysis developed and the different automation levels, for the implementation of the on-line survey and for targeting the respondents. Håkan Petersson, Damien Motte, and Robert Bjärnemo have jointly developed the questionnaires for the on-line survey and industrial interviews. Håkan Petersson and Robert Bjärnemo have visited the companies, performed the interviews, and together with Damien Motte compiled the results. Damien Motte has assisted in the structuring of the paper. Håkan Petersson presented the paper at the conference.

Also published by the author but not included in this thesis

Petersson, H. (2007). *Introduction of Composite Materials in Modern Day Production Line (In Swedish. Original title: Införande av kompositmaterial i en modern produktionslinje)*, Technical report. Lund, Sweden: Division of Machine Design, Department of Design Sciences, Faculty of Engineering LTH, Lund University.

Bolmsjö, G., Petersson, H., & Bjärnemo, R. (2008). *Robot assisted framing - A concept for securing geometry in flexible production*. 18th International Conference on Flexible Automation and Intelligent Manufacturing - FAIM 2008, Skövde, Sweden, June 30 July 2, 2008. Accepted for publishing at the conference but withdrawn available as technical report. Lund, Sweden: Division of Machine Design, Department of Design Sciences, Faculty of Engineering LTH, Lund University.

Petersson, H, 2008, *Establishment of Evaluation Criteria for Lightweight Grippers to be used in the Automotive Industry (In Swedish. Original title: Framtagning av kriterier för lättviktsgripprar inom bilindustrin)*, Technical report. Lund, Sweden: Division of Machine Design, Department of Design Sciences, Faculty of Engineering LTH, Lund University.

Petersson, H., Eriksson, M., Motte, D., & Bjärnemo, R. (2012). *A process model for the design analysis clarification task.* In P. H. K. Hansen, J. Rasmussen, K. Jørgensen, & C. Tollestrup (Eds.), *Proceedings of the 9th International NordDesign Conference - NordDesign'12* (Vol. DS 71, pp. 494-501). Aalborg, Denmark: Aalborg University.

Petersson, H., Motte, D., Eriksson, M., & Bjärnemo, R. (2012). *A computer-based design system for lightweight grippers in the automotive industry*. In *Proceedings of the International Mechanical Engineering Congress & Exposition - IMECE'12* (Vol. 3 - Part A, pp. 169-179). New York, NY: ASME.
http://dx.doi.org/doi:10.1115/IMECE2012-88067

Petersson, H., Motte, D., & Bjärnemo, R. (2013). *Carbon fiber composite materials in modern day automotive production lines - A case study*. In *Proceedings of the International Mechanical Engineering Congress & Exposition - IMECE'13* (Vol. 2A, p. V02AT02A037). New York, NY: ASME.
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Paper II: Integration of the computer-based design analysis activity in the engineering design process – A literature survey.

Paper III: The engineering designer in the role of a design analyst - An industrial survey.

Paper IV: A process model for enhanced integration between computer-based design analysis and engineering design.

Paper V: Development of a computer-aided fixture design system for lightweight grippers in the automotive industry.

Paper VI: Integration of computer aided design analysis in the engineering design process for use by engineering designers.

Paper VII: Using templates to support the engineering designer performing computer-based design analysis.

1 Introduction

In this chapter the background to the thesis project is presented and elaborated upon. From the observations made during a research project, which are accounted for in the background, the overall research question of the thesis project is established. In order to facilitate the answering of this question, it has been broken down into five sub questions or simply research questions. The establishment of necessary assumptions and delimitations associated with these research questions are introduced, and the chapter ends in a presentation of an outline of the thesis.

1.1 Background

The origin of the thesis project reported here dates back to the author's participation in a research project carried out between 2006-2008. The goal of that research project was to: "… *develop a computer based design system for the development of light weight grippers to the automotive industry*" (Rosén & L-FAM Consortium, 2009). The project was in turn one of four subprojects, or work packages, of an overall research project with the goal to "… *introduce and study novel "light weight" carbon fiber based fixtures in the assembly lines to create possibilities for: - decreased investments in assembly equipment, - an increased flexibility of assembly line planning, - a decrease of production time, - an improvement of ergonomics in manual assembly and - an increased geometrical variation of assembled products in the automotive industry*" (Vinnova, 2008, p.129).

The demand for the use of carbon fiber composites in the design of grippers was the result of a decision to keep weight as well as costs at a minimum and thus be able to maintain an already existing model of robots with lower load capacity and with access to a tailor made spot welding tool. Especially important was the access to the spot welding tool, as the robot, after having positioned the sheet metal part of the structure to be built in a locked assembly position, was expected to also carry out the actual assembly operation in the form of spot welding. The prototype production cell for the assembly of truck cabs is shown in Figure 1.1.

Figure 1.1 The prototype production cell (Rosén & L-FAM Consortium, 2009).

One of the major difficulties in the development of the computer-based design system was the adaptation of the design system to the intended category of users of the system, who in the automotive industry are traditionally production engineers. Another major difficulty in the development of the design system originates from its focus on light weight designs made of carbon fiber composites. Initially, this implies that the system user is expected to possess detailed knowledge of the material properties and behavior and of the very special design solution rules and paths to follow in the synthesis part of the engineering design process, or simply design process for short. The single most complex, and thus difficult part in the design process, is how to perform the design analysis activities, as they presume the use of computer-based structural analysis tools such as Finite Element Analysis (FEA) and computer-based structural optimization, mainly due to complex geometry and the need for utilizing advanced constitutive modeling of the carbon fiber composites. As a consequence of these difficulties, the subsequent engineering design process activities such as the evaluation of and choices between the proposed design solution candidates, also cause additional problems of the same origin. In short, the computer-based design system should "fill in" all of the gaps of insufficient knowledge and experience in creating carbon fiber composite design solutions and in the analysis and optimization of these by means of computer-based analysis tools.

In order to fulfill all of these demands on the computer-based design system, the first step to be taken was to pre-develop parameterized design solutions to be used and made available to the system user on different levels of concretization during the synthesis activities. The second step was to provide the computer-based design analyses and optimization tools necessary for the analyses and optimizations utilized for the subsequent evaluation and selection of the final design solution. The implementation of these methods and tools into industrial practice is here referred to as Computer-Based Design Analysis (CBDA) or design analysis for short - as long as this abbreviation is unambiguous. Note that the optimization tools are here assumed to be provided within the Finite Element (FE)-program packages. As for the CBDA and optimization activities, all of them needed to be pre-developed and available to the user in a form which eliminates the user's lack of skills and insights into these areas. An important tool to facilitate an easy and safe handling of the system was accomplished by the introduction of a Knowledge Based Engineering (KBE) system. The active support provided by the KBE system guides the user in all of the essential decisions throughout the entire engineering design process. Thus the design system became more or less fully automated regarding the activities which needed specialized knowledge and skills, while the easier tasks as the supply of input data was performed "manually" by simply feeding the requested data.

The final results of the complete research project are accounted for in (Rosén & L-FAM Consortium, 2009), and the development of the computer-based design system is described in some detail in (Petersson, Motte, Eriksson, & Bjärnemo, 2012).

In order to accommodate the high level of automatization required in the computer-based design system, an extensive use of templates was the obvious choice. In the given context, a template refers to an especially pre-formatted code, which contains the implemented information/knowledge necessary to perform a specific task on an operational[1] level. It should be noted that the use of templates as a means of support in performing a specific design or analysis task is not a new phenomenon in industrial practice. One example is the templates provided in the Ansys program (ANSYS, 2015) to facilitate the handling of the actual analysis process, another is the use of templates to describe models of expert knowledge in KBE-systems (Breuker & Van de Velde, 1994; Schreiber et al., 2000). However, in the development of the computer-based design system the use of templates was, in a strict sense, also to support, though more in the meaning of "compensating" for the user's lack of knowledge and experience. In this interpretation of support, the use of templates in the described context differs significantly from the more "traditional" use of templates.

The current trend in industry to engage engineering designers to take an active part in the design analysis of their own design solutions is apparent in many companies

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[1] Here refers to the level of abstraction of the work performed in solving a specific task derived from the activities identified as having to be carried out during the actual analysis process.

today, domestically as well as abroad. In a survey by Lees and Wood, (Lees & Wood, 2011) it was found that the "lack of skills", along with "recruitment", are the single most conclusive factors in allowing engineering designers to actively participate in CBDA. In a report on the experiences drawn from simulation and practices in 488 Best-In-Class organizations to address optimal profitability, it was found that increased collaboration between simulation experts and novices together with the need to capture the expertise of simulation veterans were two of the five most important strategies recommended (Aberdeen Group, 2013a).

Inspired by the opportunities provided by the template approach to facilitating some, if not all, of these objectives, resulted in a decision on the thesis project reported here. The ***main objective*** set out for this project was to ***facilitate the engineering designers' active participation in performing CBDA singlehandedly, or in any other organizational setting, by utilizing a Template-Based Design Analysis (TBDA) approach, as an integrated part of their activities within the engineering design process.***

It is essential to note that a TBDA approach is not confined to the development of suitable templates. In its initial context, in the computer-based design system, the TBDA approach includes the following activities:

- Decision on whether or not to develop a TBDA approach, as this presumes a repetitive design analysis process focusing on a specific type of product – ranging from a complete design system, as described above, to the embodiment of a detail in a part of an overall design solution.
- Identification of those activities from the engineering design as well as from the CBDA processes to be included in the TBDA approach.
- Development of the actual TBDA approach, including development of the templates and additional tools, by means of method or technology development.
- Software implementation of the TBDA approach, and training of the users of the TBDA approach.

Note that the term *approach* has been used instead of *process* because the present contents and connections between the activities are yet not fully determined.

1.2 Research questions

The main issue in focus of the thesis project, in other words, is to investigate the potential provided by the TBDA approach to compensate for insufficient or no knowledge and/or experience of CBDA in industrial engineering design practice. Since engineering designers are already today actively participating in CBDA, it is equally important to position the TBDA approach in comparison with other similar approaches and thus find arguments for and against an industrial introduction of the approach.

The ***MAIN RESEARCH QUESTION*** *to be answered in this thesis project can be formulated as follows:*

Does the TBDA approach provide sufficient support to become a competitive approach in engineering design practice in comparison with existing approaches utilized by engineering designers in performing CBDA singlehandedly or in any other organizational setting?

In order to answer this complex question, it is necessary to be able to handle the inherent complexity of the question. This is done by breaking it down into five sub questions, or simply research questions.

We have previously described how engineering designers are already today performing CBDA in industry. It is therefore important to acquire a deeper insight into the present practice utilized by engineering designers in performing CBDA activities in industrial practice. In order to avoid too narrow a view of this issue, it is important to broaden the question to a more general question on how CBDA today is performed in industrial practice. It is thus important also to recognize the potential impact of different organizational settings in the industry, such as SMEs and large companies as well as consulting companies offering their services to such companies. For practical reasons it is initially practical to confine such an industrial survey to the Swedish industry. An important aspect of the industrial survey is to clarify the organizational structure of the actual design and development processes within which the engineering designers have to perform CBDA, since those processes can be expected to differ significantly between companies. The fact that engineering design and design analysis process models are utilized in most companies does not automatically mean that interaction between these process models is facilitated in a way which results in an efficient and effective work process for complex design and analysis tasks. The question whether the companies utilize integrated process models or not is thus of utmost importance, as these models are instrumental in identifying the activities in which engineering designers might be involved. In parallel with the industrial survey it is also necessary to perform a literature survey on CBDA in industrial practice.

THIS RESULTS IN THE FIRST RESEARCH QUESTION: How is CBDA performed today in theory as well as in Swedish industry, and is the current practice supported by integrated process models between CBDA and engineering design?

In order to extend the insights into the industry, companies abroad need also to be examined. It is also important to make an inventory of all existing approaches to support the engineering designer in performing CBDA. For practical reasons, this extended survey is expected to be carried out in the form of an on-line survey, thus facilitating a coverage of the international manufacturing industries and consultants which is as extensive as possible. The selection of companies, for obvious reasons, is very difficult, and so requires the active help of international engineering organizations to promote the survey to its members or member organizations.

THIS RESULTS IN THE SECOND RESEARCH QUESTION: How is CBDA performed today in the international industry and which current practices are utilized in supporting the engineering designer to perform the CBDA activities - including integrated process models?

Based on the results obtained from the two preceding research questions and the results obtained from the literature survey, it should be possible to establish whether or not integrated process models are at hand for implementation in industrial practice. If so, adaptation of such a model to TBDA is to be carried out, if needed. If integration models are not to be found, the development of such a model should be carried out.

THIS RESULTS IN THE THIRD RESEARCH QUESTION: Does an integrated process model exist which can be utilized as a platform within the TBDA approach or is it necessary for us to develop such a model of our own?

In parallel with the surveys on the TBDA approach, demonstrator projects in close cooperation with industry have been performed in which TBDA as a tool has been adapted to a number of different industrial settings. The first example of this is the computer-based design system described in the background section. In that example, the objective was to develop a complete design system which could be characterized as a fully automated system. A detailed account of the development of the system will be provided below. The additional demonstrator projects focus on other industrial settings, such as the design synthesis and design analysis of components and details. By performing these projects, a deeper understanding and insight into the actual TBDA activities on an operational level are expected, which in turn are expected to contribute to a deeper knowledge and insight into the TBDA approach as such. The possibility to verify whether or not the analysis results obtained using the TBDA approach are compatible with the results obtained using other approaches is also an important outcome from these projects.

THIS RESULTS IN THE FOURTH RESEARCH QUESTION: How might the information derived from a number of demonstrator projects contribute to an increased knowledge and insight into TBDA on an operational level?

Based on the results obtained during the surveys in industry and of the literature in combination with the knowledge and insights drawn from the demonstrator projects, the main characteristics of the TBDA approach are established.

THIS RESULTS IN THE FIFTH RESEARCH QUESTION: What are the main characteristics of the TBDA approach in terms of usage, issues related to its development and implementation, impact on development projects, challenges and future developments?

1.3 Assumptions and delimitations

The following assumptions and delimitations have been applied to the research project:

- The application area for which TBDA is established is confined to the area of mechanical engineering.
- The developments of the TBDA cases presented are all subjected to restrictions emanating from the industrial partner. This not only constrains the actual performing of the projects, but also the possibilities to fully present all aspects of the projects.
- The methodological aspects of software development related to templates have not been thoroughly investigated, although some elements are mentioned, such as costs, necessary resources, and architecture.
- The industrial case projects have all been carried out utilizing the software CATIA V5 including its integrated solutions to KBE systems and Computer Aided Design (CAD)/Computer Aided Engineering (CAE).

1.4 Outline of the thesis

Chapter 1– Introduction

This chapter introduces the background to the thesis project, the main research question and the five research questions into which the main research question was broken down. The assumptions and delimitations emanating from these research questions are also accounted for.

Chapter 2 – Research process

In this chapter the introductory and linear parts of the research process are described.

Chapter 3 – Frame of reference

In this chapter, the body of research upon which this thesis is based is reviewed.

Chapter 4 – Summary of appended paper

This chapter contains the results of the appended papers and their contributions to the answering of the research questions.

Chapter 5 – Conclusions, recommendations and perspectives

In this chapter, the answer to the main research question is given. Based on this answer, conclusions are made whether or not the answer fully covers all aspects of the research question. Following that, additional aspects on TBDA are presented. Recommendations for the implementation of TBDA in industrial practice and items of importance for future research projects of the TBDA approach conclude the chapter.

References

Appended papers

2 Research process

This chapter begins with an account of the introductory part of the research process which took place before the thesis project was formally established. After the establishment of the thesis project, the subsequent part of the research process is of a linear, evolutionary nature.

2.1 The introductory part of the research process

As described in section 1.1, the Background, the thesis project originates from observations made during a research project with the goal to develop a computer-based design system for light weight grippers to the automotive industry (Rosén & L-FAM Consortium, 2009). This research project was initially intended to become the basis project for the author's Licentiate of Engineering thesis and subsequently of his doctoral thesis. A number of factors, chiefly proprietary considerations raised by some of the participating companies, were of such a severe nature that they made it difficult, if not impossible in some cases, to publish all of the findings from the project. They also made it quite impossible to continue the project towards a doctoral thesis. In spite of these difficulties, it has been possible to publish a conference paper describing the computer-based design system (Petersson et al., 2012). An extended version of that paper, in the form of a journal article, is currently under revision as **Paper V.**

Since observations of the potential provided by the template approach were made already during the execution of the project, and the difficulties accounted for above were already a reality to be taken into account, a preliminary plan to further investigate the template approach was established. As a first step, the opportunity to participate in a survey in Swedish industry was accepted. The industrial survey project was initiated by M. Eriksson, at the time also a PhD student at the Division of Machine Design at Lund University. Eriksson's PhD project focuses on the development of a methodology for Predictive Design Analysis (PDA) (Eriksson, 2015), in which this survey played an important role. The survey focused on the interaction between CBDA and the engineering design process in Swedish industry. The expected findings from this project were of major significance in order to gain a broad perspective on how CBDA is performed in industry and thus also on the activities in which engineering designers might be involved in CBDA. For the execution of the survey a survey technique based on a combination of a questionnaire and an interview was chosen. This has been proven successful in similar surveys in industry by (Bjärnemo, 1991) and (Bramklev, Bjärnemo, & Jönson, 2001). The results including a complete account of the survey technique is presented in **Paper I**.

In addition to the industrial survey, a literature survey was performed to give an overview of the current state of the art regarding the integration of the CBDA activities into the engineering design process. The review method applied has been to manually scan the titles of publications, proceedings and journals in search of papers describing processes, methods or case studies that could be connected to the process integration theme and to utilize the lists of references of relevant papers identified to find new publications. The results including a complete account of the survey technique is presented in **Paper II**.

As a first attempt to explore the potential provided by the template approach, a case study was performed in close cooperation with industry and published in **Paper VI**. That paper contains a first, preliminary description of TBDA.

Based on the research projects accounted for above it was possible to establish the objective of the thesis project and thus of its corresponding main research question and the five research questions into which the main question was broken down.

The reasons accounted for above, explains why publishing dates and the order, in which the appended papers are presented, do not follow in the expected order.

2.2 The linear part of the research process

The linear part of the research process started when the thesis project was formally established, which was done at the end of 2013. The reference to a linear process refers to the fact that this part of the process follows the consecutive order in which the research questions are answered. This part of the research process might also be characterized as being of an evolutionary nature, indicating that results are derived from the answers to the research questions and used in the gradually evolving result of the research process.

The introductory part of the research process included the answering of the first research question, which means that there is an overlap between the two parts of the research process. For reasons of clarity, the answer to that question will be mentioned in the presentation of the linear part of the research process given below.

Regarding the first research question (“*How is CBDA performed today in theory as well as in Swedish industry, and is the current practice supported by integrated process models between CBDA and engineering design?”)*

This part consists of the two surveys, the survey in Swedish industry and the literature survey – accounted for in **Paper I** and in **Paper II.**

Regarding the second research question (“*How is CBDA performed today in the international industry and which current practices are utilized in supporting the engineering designer to perform the CBDA activities - including integrated process models?”)*

The approach chosen to answer to this question is also to perform a survey in industry, but now in an international perspective. The expectations are almost the same as for the survey in Swedish industry, but with the exception that in this survey TBDA is introduced and specific questions are expected to be answered by the companies claiming that they are using TBDA.

This survey calls for a totally different approach, as the practical problems associated with this survey are no longer confined to terminological issues but also to how to establish a way of communicating with the respondents as well as selecting respondents in the international arena, to mention just a few of the difficulties.

The approach selected was to utilize an on-line survey technique, described at the home page www.quicksearch.se, in combination with collaboration with the international engineering organizations American Society of Mechanical Engineers (ASME), Design Society, LinkedIn and NAFEMS (originally National Agency for Finite Element Methods and Standards). These organizations were expected to introduce and promote the survey through different channels. An announcement was made on the home pages of NAFEMS and the Design Society, and an article in NAFEMS magazine Benchmark was published. Postings in different member groups within ASME resulted in 15 respondents and LinkedIn in 35. Networks were established and a set of companies, mainly selected from the earlier industrial survey (**Paper I**), were invited to answer the questionnaire.

The on-line survey consisted of two different surveys. The first one was a direct continuation of the set of interviews conducted in the survey in Swedish industry (**Paper I**) and contained a maximum of 73 questions, divided into eight different categories, depending on the answers from the respondents. Focus in the first survey was mainly on the usage of CBDA by engineering designers within the respondents’ companies and what type of processes they were using for engineering design and design analysis. The outcomes of this survey are reported in **Paper III**. The second survey is accounted for in **Paper VII** – see regarding the fifth research question below.

Regarding the third research question (“***Does an integrated process model exist which can be utilized as a platform within the TBDA approach or is it necessary for us to develop such a model of our own?”)***

The answer to this question is based on the findings from the previous research questions, whether or not an integrated process model is available for adaptation, if necessary, to the TBDA approach. The result was rather straightforward – no such integrated process model was to be found in the literature, nor was there any such process model available in industrial practice even though a number of respondents claimed that they were using such models. As a consequence of this result, the development of an integrated process model was initiated in close collaboration with M. Eriksson.

The goal set out for this process model was to provide an integrated process model for CBDA facilitating interaction between CBDA and engineering design processes on an operational level; the process model should also be implementable in industrial practice as well as in the training of new generations of design analysts and engineering designers. The process model needs also to be both adaptive and generic – here to be understood as not being dependent on any specific engineering design process model and/or of any specific type of product.

An additional publication of great importance for the development of the integrated process model, not included in the thesis project but related to it, are presented in (Eriksson, M. & Motte, D., 2013b). Another work tries to eliminate some integration issues through the use of quality assurance (QA) techniques and procedures (Eriksson, M. & Motte, D., 2013a), which deals with factors exogenous to the design analysis activity.

The process model provides an operational tool to be utilized in the planning and analysis of the integrated activities occurring during the CBDA and the engineering design processes. The adaptive as well as the generic nature of the process model developed, the Generic Design Analysis (GDA) process model, makes it an excellent tool for identifying activities and developing TBDA tools needed for a specific project or category of projects in industrial practice. The GDA process model is presented in **Paper IV**.

Regarding the fourth research question (“***How might the information derived from a number of demonstrator projects contribute to an increased knowledge and insight into TBDA on an operational level?”)***

As previously mentioned, demonstrator projects utilizing TBDA have been performed both before and after the establishment of the thesis project. The first of these is the computer-based design system described in the background section - a detailed account of the development of the system is provided in (Petersson et al., 2012) - and in **Paper V.** In the additional demonstrator projects focus is on other industrial settings – see **Paper IV** (in which the same case as presented in **Paper VI** is addressed but now with focus on identifying the activities utilizing the GDA process model on which the establishment of the actual TBDA approach is to be built), **Paper VI** and **Paper VII.** The expected outcome of studying these projects is primarily a deeper understanding and insight into the actual TBDA activities on an operational level.

Regarding the fifth research question (“***What are the main characteristics of the TBDA approach in terms of usage, issues related to its development and implementation, impact on development projects, challenges and future developments?”)***

Based on the results obtained during the surveys in industry and of the literature in combination with the knowledge and insights drawn from the demonstrator projects, the main characteristics of the TBDA approach are established.

The second on-line survey, mentioned in the second research question above, was related to the use of CBDA by the engineering designers with a focus on their usage of the different types of support, especially the usage of templates by the engineering designers in the industry. The second survey contained a maximum of 34 questions and was like the first survey divided into eight different sections. Focus on the second survey was on different types of support for the engineering designer while performing design analysis with a deeper focus on TBDA. The whole study was completed with personal interviews in a number of selected companies in Sweden. The results from the second survey and the personal interviews are reported in **Paper VII**. This paper also gives a general overview of TBDA in industry and touches upon: the implementation of TBDA, the usage of TBDA, the different types of templates used (from basic to fully automated) the types of analysis performed using templates, exemplified with industry cases, issues related to TBDA and the impact of TBDA for engineering designers, design analysts and the company as a whole.

3 Frame of reference

In this chapter, the body of research upon which this thesis is based is reviewed. It intends to ease the understanding of the research scope and results presented in the next chapter. Note that several of the subjects are further elaborated upon in the appended papers. The core subjects of interest are those which are initially identified in the main research question and the five research questions, namely: engineering design process models, CBDA, integration of CBDA with the engineering design process, KBE systems and subjects emanating from the survey results and interviews which needs to be elaborated upon in order to establish a theoretical platform for each of these.

3.1 Engineering design process models

For the implementation of TBDA, it is essential that it should be possible to identify the activities in the engineering design as well as in the CBDA processes for which templates should be developed to facilitate for the engineering designer to perform CBDA singlehandedly or in any other organizational setting. Today, engineering design is predominantly taught as an engineering subject, which is a major step from the older tradition in which engineering design was considered a natural talent rather than something that could be learnt. When taught, focus was set on providing examples of "good and successful" designs, from which the future engineering designer should extract insights which could be of major importance when he/she in the future should design new products on their own. In Germany this was referred to as "konstruieren nach Vorbildern" – i.e. roughly "designing from examples".

Today, a number of engineering design process models are available to be adopted or to be used as platforms in companies in the development of such models of their own to tailor them to their own specific conditions. Examples of engineering design process models in literature are: (Cross, 2008; Eggert, 2005; Otto & Wood, 2001; Pahl, Beitz, Feldhusen, & Grote, 2007; Ulrich & Eppinger, 2012; Ullman, 2010).

In Figure 3.1 the engineering design process by Pahl and Beitz is presented.

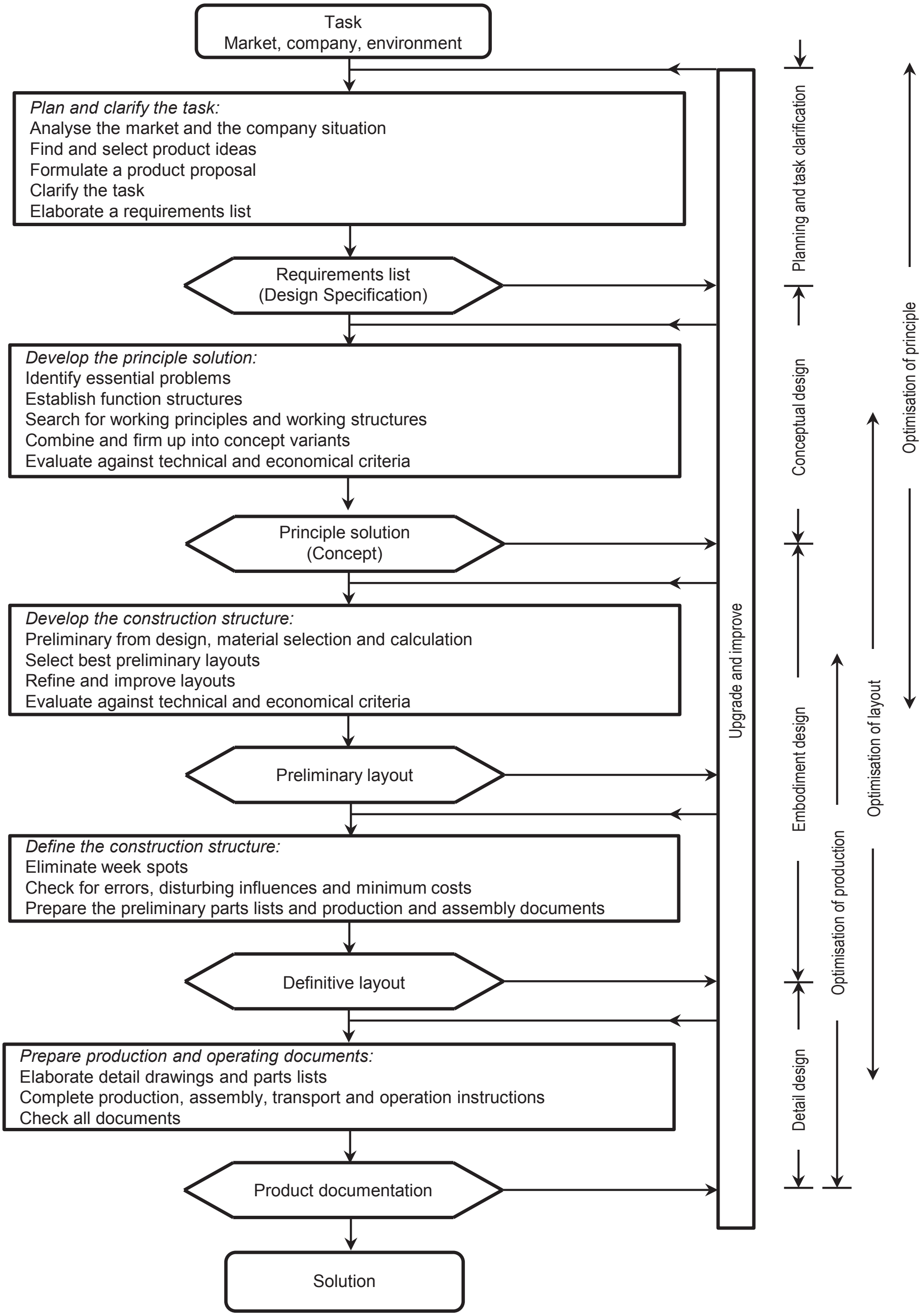

Figure 3.1 The engineering design process by (Pahl et al., 2007, p. 130).

In a somewhat more philosophical vision of design, (Simon, 1996) makes a comparison between science and design in which the author points out that science is concerned with generating knowledge related to natural phenomena and objects, while design is concerned with creating knowledge related to phenomena and objects of the artificial. An operational interpretation of the nature of engineering design adopted here is to consider engineering design as a process starting from a predefined setting that might range from a material need to a well-defined technical solution or principle ending up in a set of documents utilized for the materialization (manufacturing/production) of the product-to-be. During this process a number of iterative synthesis-analysis-evaluation loops are carried out.

Product development in its industrial setting is regarded as a multifunctional process that includes, as a minimum, the following sub functions: marketing, design and manufacturing/production (Andreasen & Hein, 1987; Ehrlenspiel, 1995; Olsson, Carlqvist, & Granbom, 1985; Ulrich & Eppinger, 2012). In the academic setting multifunctional is often referred to as multidisciplinary. The process presented by Olsson and denoted *Integrated Product Development* (Olsson et al., 1985) involves four sub processes (marketing, design, manufacturing/production, and business/financing) as described in Figure 3.2.

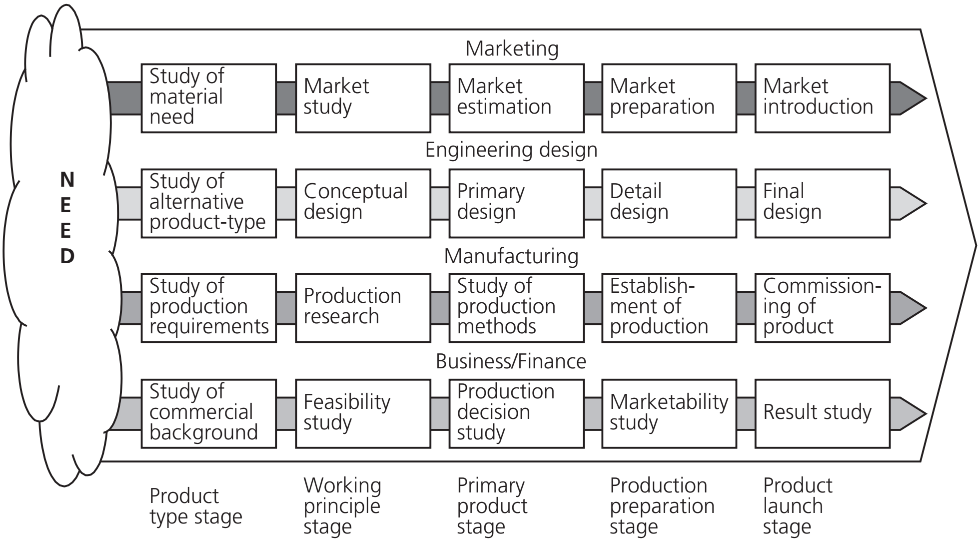

Figure 3.2 Integrated Product Development by (Olsson et al., 1985).

3.2 Computer-Based Design Analysis (CBDA)

Before introducing CBDA process models found in the literature, it is important to further clarify the concept of CBDA. As CBDA can take a multitude of forms, including methods and tools of both a qualitative and a quantitative nature, it is important to confine it to its current use, which is within quantitative analysis originating from design and development of new or improved products or from redesign of existing ones.

A prerequisite is that the physical phenomena should be computationally solvable with current state of the art CAE methods and tools, such as Computational Structural Mechanics (CSM), Computational Fluid Dynamics (CFD) and Multi-Body Systems (MBS). CSM is a common denominator for methods and tools applicable for structural analysis including the Finite Element Method (FEM). In industrial practice, the CAE methods and tools are frequently utilized together with different complementary techniques such as Design Of Experiments (DOE), KBE, optimization (by methods such as approximation methods, evolutionary algorithms and gradient based methods for e.g. size, shape and form and topology optimizations performed as single- or multi-objective as well as single- or multi-disciplinary).

3.2.1 CBDA process models

Here, the presentation of CBDA process models is to be confined to those based on the utilization of FE-based tools. When numerical design analysis methods such as FEM were introduced for a broader audience in academia and industry, the main focus was on how to solve established numerical problems accurately and efficiently by utilizing a number of procedures, methods and techniques. Such procedures can be found in works by (Bathe, 1996; Belytschko, Liu, Moran, & Elkhodary, 2014; Chopra, 2012; Cook, 1995; Cook, Malkus, Plesha, & Witt, 2002; Fish & Belytschko, 2007; Liu & Quek, 2003; Zienkiewicz & Cheung, 1967; Zienkiewicz, Taylor, & Zhu, 2005), to mention just a few of the vast variety of publications connected with FEM.

In the design analysis literature, a number of design analysis process models are presented that are fairly similar in their decomposition into phases, but differ when it comes to the individual steps or activities forming each of these phases. Two examples of analysis processes are presented below.

The analysis process model by (Bathe, 1996) presented in Figure 3.3, starts from a predefined physical problem that is translated into a mathematical model, which in turn is translated into a solvable FEA formulation. Resulting from the solving/execution of the FEA problem, the results undergo an assessment of the accuracy (verification) of the mathematical model. If the result of this investigation is satisfactory, the results are interpreted and downstream activities such as design improvements and/or optimization follow.

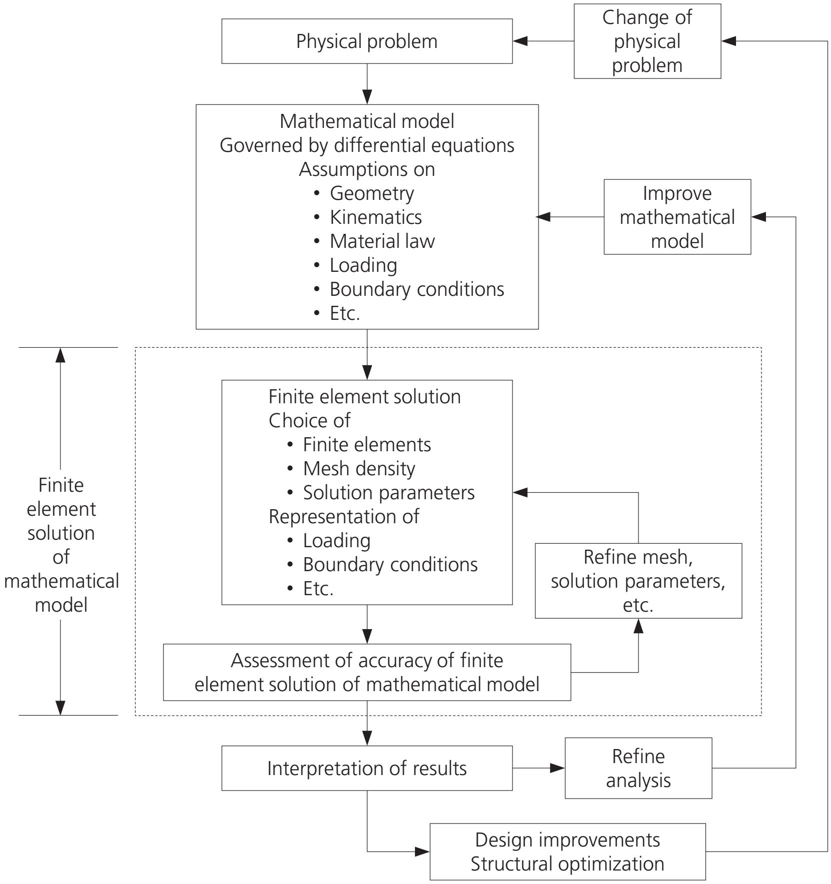

Figure 3.3 Outline of a FEA task according to (Bathe, 1996).

With the further development of software and generalization of the use of such numerical methods, process models have been gradually developed that encompass industrial aspects in order to support the practitioner's work. NAFEMS has proposed several such models during the last few decades that are intended for practical implementation in industrial practice.

In *How to Plan a Finite Element Analysis* (Baguley & Hose, 1994), the workflow of design analysis tasks includes steps that couple analysis to the development project: it includes for example tasks that are project- and company-related: preparation and agreement of specification of the task, preliminary calculations in order to provide resource estimations etc. as shown in Figure 3.4 . The workflow is concluded with information feedback in terms of presentation and reporting.

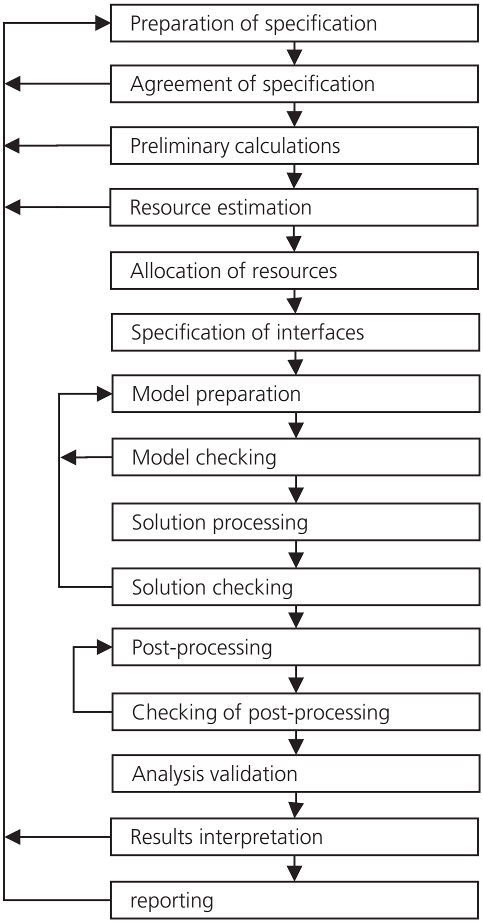

Figure 3.4 Workflow of an FEA outlined by NAFEMS (Baguley & Hose, 1994).

These process models present roughly the following structure: analysis planning, execution (also called solution processing) and result interpretation and communication.

3.2.2 Relevance of CBDA

The significance of the CBDA process within the engineering design and product development processes is well established. In the NAFEMS Simulation Capability Survey 2013 (Newton, 2013), the results from 1115 respondents show that design analysis is now used in all phases of a product development project, with 29% of all analyses performed during the conceptual design phase. In (Aberdeen Group, 2013a) and (Aberdeen Group, 2015a), 74% of the respondents answered that it is important to use simulation early in the product development process making it easier to handle complex products and get the design right from the beginning. The *Industry needs survey report* (Lees & Wood, 2011), with a total number of 1094 respondents from 50 different countries, 98% answered that FEM is important and 82% of those answered that it is very important in the field of analysis. FEM is also top ranked as regards what companies find an important analysis area. In industries developing complex systems, such as the automotive industry, the use of simulation is now indispensable (AutoSim, 2015).

Finally, (Adams, 2015) lists 5 objectives constituting important benefits from using FEM, namely reduce development time; increase innovation; reduce product costs; reduce development costs and improve product quality.

3.3 Integration of CBDA with the engineering design process

The main focus here is to provide for an efficient and effective integration, at an operational level, between relevant activities within the engineering design and the CBDA processes. Integration of this nature is usually referred to as integration at an organizational level.

As shown in the literature survey in **Paper II**, most well-known publications describing engineering design/product development processes, such as (Cross, 2008; Eggert, 2005; Otto & Wood, 2001; Pahl et al., 2007; Ulrich & Eppinger, 2012; Ullman, 2010), do not emphasize design analysis activity in their process models. The exceptions from the German literature are (Ehrlenspiel, 1995), the German versions of (Pahl & Beitz, 1977), and the VDI Guidelines 2221 of 1993 (VDI, 1993) and 2211-2 of 2003 (VDI, 2003a). Design analysis is mentioned in (Pahl & Beitz, 1977; Pahl, Beitz, Feldhusen, & Grote, 2005) in a specific chapter on computer-supported engineering design, where computer-based tools are introduced in the general engineering design process model. The part concerning analysis is not very detailed and chiefly descriptive. (Dieter & Schmidt, 2013) describes 5 steps in what they call Parametric Design, but it does not refer to design analysis. A number of publications outlining design systems, such as (Saxena & Irani, 1994), were found—also including projects from our own research within the area such as (Wang, Eriksson, & Bjärnemo, 2007). However, in none of these is the interaction between the design/development activities and the CBDA activities described at an operational level suitable for implementation in a design system of the kind to be developed here.

When studying the literature on methodologies for CSM, such as (Zienkiewicz et al., 2005; Cook, 1995; Bathe, 1996), which are the most commonly referenced studies comprising theories on FEA and FEM, the connections between the engineering design and design analysis activities are not developed. NAFEMS has proposed several models during recent decades that have been influential in industry. Other subsequent works are (Adams & Askenazi, 1998; Liu & Quek, 2003; Adams, 2006). In (Dolšak & Novak, 2011), two features, Design Candidate and Proven Design, are part of the integration of design analysis with the engineering design process. Figure 3.5 shows that it is the user that is the hub of the integration between redesign and FEA process.

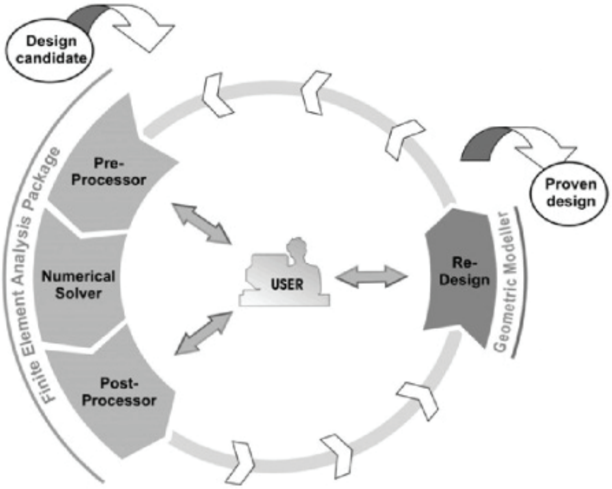

Figure 3.5 FEA as part of the design improvement cycle (Dolšak & Novak, 2011).

Finally, some works discuss the implementation of design analysis in the engineering design activity so that the whole process is more efficient and proceeds without friction. (King, Jones, & Simner, 2003) present a "good practice model" for implementation of CBDA in product development. But there is no model presented at an operational level.

3.3.1 Adaptation of CBDA software for the use by the engineering designers

CBDA has been used for many years within the industry, and the normal procedure is that the engineering designer sends the digital information on the design solution developed to the design analysts for an investigation of its mechanical properties. In later years, more software developers have started to integrate more advanced CAE (FEM) capabilities into their CAD systems which make it accessible for a wider target group. One of those targets is the engineering designers and by introducing CBDA for the engineering designers some new possibilities have been discovered. In an industrial case at Ford Motor Company (Hardee, 2010), the software chosen as the integrated CBDA tool was Abaqus For Catia (AFC). The outcomes from the case are that by using only one interface for both design and analysis activities the analysis process has been accelerated, multiple iteration can be done more quickly and, as there is no delay between the steps they get a more streamlined workflow. The importance of the integration of CAE tools is also confirmed in a report presented by the Aberdeen group (Aberdeen Group, 2015a) where the opportunity to perform simulation (CBDA) integrated with CAD was listed as important (70%) and so was the opportunity to perform simulation early in the design process (73%) which made it possible to improve assessments of design solutions earlier in the design process. These findings were also confirmed in the *NAFEMS Simulation Capability Survey 2013* (Newton, 2013) in which the respondents answered that it is important to use simulation early in the design process but here also referred to in terms of the phase in which the simulation was performed - 29 % answered in the concept phase and 45% in the engineering design phase (engineering design phase is a term introduced by NAFEMS). In the same report it is also shown that it is not an easy task for the engineering designers to adopt these new features. Lack of skills and experience and an inability to obtain reliable data are the two major issues regarding the impact of introducing CBDA on a broader front.

3.3.2 Software integration

Suppliers of advanced CAD systems are providing imbedded CAE capabilities today, as the integration of CAE with CAD systems partly or fully eliminates the differences in model representations of geometry and analysis. This requires more extensive support for CBDA (Lee, 2005), and knowledgeware has to be more integrated for support and quality assurance (Petersson et al., 2012; Kraft & Nagl, 2007; Kraft & Nagl, 2007). The outcome of CBDA, in terms of quality, effectiveness and reliability, depends on the designer's knowledge and experience (Dolšak & Novak, 2011). There are some vendors that deliver software packages that have integrated Finite Element capabilities such as Parametric Technology Cooperation (PTC), SolidWorks, Siemens, Dassault Systèmes and Simulia.

Although these software products have integrated FE capabilities, there are still some limitations. The setup of the software is dependent on the different processes within the company's Product Lifecycle Management (PLM) system, and the actual setup has to be done by following them, see sections 5.2 and 5.3.1.

3.4 Knowledge Based Engineering (KBE)

In the TBDA concept KBE systems play a major role in overcoming the lack of knowledge and insights into CBDA on behalf of the engineering designer.

KBE can be defined as "[t]he use of advanced software techniques to capture and re-use product and process knowledge in an integrated way", according to MOKA (Stokes, 2001, p. 11). KBE is the bridge between knowledge management and design automation and plays an important part in advanced computing.

The predominance of routine tasks in the design process is the main reason for using KBE systems. According to (Stokes, 2001) and (Callot, Kneebone, Oldham, Murton, & Brimble, 1998), the percentage share of routine tasks in designing processes represents about 80%. With the help of KBE, design time is significantly reduced, see Figure 3.6. Apparently, it is an estimated value, and the final share of routine tasks depends on an individual design. KBE has become even more important as the digital design software extends its development. Functionality becomes more and more powerful and is a valuable support when implemented in the software. Within engineering design, KBE is basically used as a support methodology for the development of automated design tools.

When knowledge management modules are implemented in a CAD system, it allows control of many different types of features. By creating geometry, securing processes and being able to supervise and govern, time can be saved and quality assurance and other conditions can be fulfilled. KBE has become even more important as the digital design software extends its development. Functionality becomes more and more powerful and it is a valuable support when implemented in the software and used for developing design systems. Using full integration of KBE, design analysis (Chapman & Pinfold, 2001) and optimization (Kuhn, Liese, & Stjepandic, 2008) of parameterized models give great advantages if the geometric model is suitable. Catia V5 and the knowledgeware module is an example of a CAD system that is able to store and reuse knowledge.

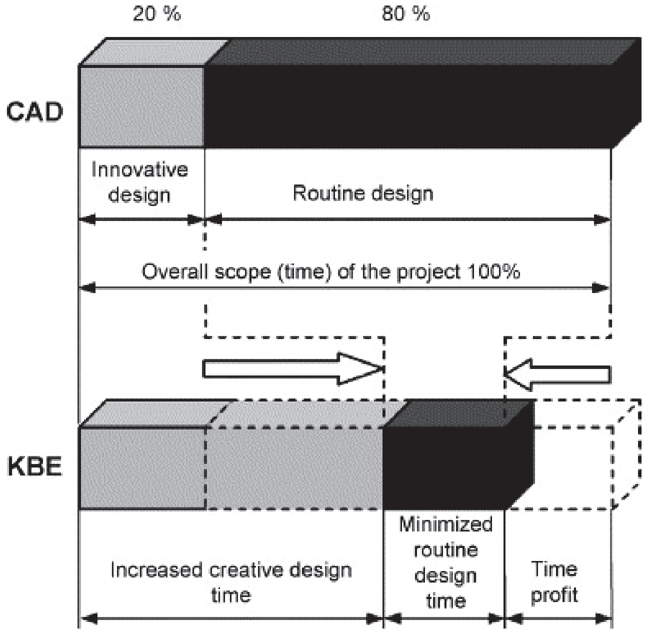

Figure 3.6 Influence of KBE usage on time of main design tasks (Skarka, 2007).

KBE may be considered an important approach for the development of templates for CBDA. Some applications of KBE in domains similar to this study have been found. (Johansson, 2008, p. 51) describes how KBE can be used in combination with both optimization and design analysis. Another application is the Design Analysis Response Tool (DART), (Chapman & Pinfold, 2001), a KBE tool used for the generation of FE surface meshes to a BIW product in the automotive industry. KBE is used for applying the thickness (a "representative” thickness) to the surfaces and to the analysis model’s shell elements by using surfaces (shells) instead of volumes (thin-walled solids), to limit the time required for analysis while maintaining good quality of the results.

3.5 Subjects emanating from the survey results and interviews accounted for in the appended papers

In order to investigate the current knowledge available in literature emanating from some of the specific areas introduced in appended papers, these are accounted for below.

3.5.1 Supervision by a design analyst

The type of support that is most frequently used (**Paper VII**) in companies is supervision by a design analyst, and it is appreciated by the engineering designers as well as the company. One example of a successful outcome of the supervision between "engineering designers" (students) and a design analyst is the development of an engine bracket (Landqvist & Petersson, 2013). The importance of this kind of collaboration is also recognized in the report *Eliminating simulation bottlenecks with best in class meshing* (Aberdeen Group, 2015b). In the results from the survey shows that promoting collaboration between analysis experts and design engineers is one important approach in supporting the engineering designers while performing design analysis. This type of support is valuable as it strengthens the engineering designer's confidence to perform design analysis and, at the same time, presents the type of challenge that the engineering designer needs for his/her own motivation. Finally, in (Lees & Wood, 2011), the highest ranked method to evaluate the skills achieved by the design analyst was internal assessment by the manager/mentor.

3.5.2 Specialized education/training

Training or educating the engineering designers is important in many aspects. From the survey (**Paper VII**), respondents reported that it is hard to motivate engineering designers to stay with the company. By introducing training, it is possible to increase the engineering designers' motivation (Aberdeen Group, 2013b). It is also mentioned in (Lees & Wood, 2011), that 71% of the respondents are using CAD/CAE integrated software, which shows the importance of also introducing interface/integration competencies in the educational base. This is also confirmed in (Aberdeen Group, 2013b) and in (Aberdeen Group, 2006) where best-in-class manufacturers are 63% more likely to provide CAD-embedded simulation to their engineers, as software training is recommended in order to reduce the technological barriers of performing simulation for non-expert and infrequent engineering users. The training program contains training material and specific examples to get users up to speed. In (Lees & Wood, 2011) it is confirmed that among the barriers to using CBDA, the highest rated were "recruitment" and "lack of analysis skills", clearly indicating a need for improved lifelong learning.

Several authors discuss the importance of properly educating engineering designers in design analysis in order for them to be able to make their own preliminary analyses with an awareness of recurrent pitfalls in that area and to be able to communicate with specialists (Adams, 2001; Meerkamm, 2011).

3.5.3 Guidelines

Guidelines have been used in industrial practice for many years. Especially in Germany, guidelines are used extensively for many frequent design tasks, such as designing a bolted joint ref (VDI, 2003b). Similar types of guidelines are also used on a daily basis by many engineering designers and design analysts in CBDA.

The guidelines are normally used for repetitive and advanced types of design analyses, e.g. welds and rivets, and require some fundamental knowledge and insights of the user of the guidelines. This is due to the fact that guidelines are to be interpreted and applied and not strictly followed, as templates are. It should be noted that guidelines are also introduced for design analysts in avoiding and thus eliminating different approaches to a given design analysis task.

3.5.4 Templates

In (Aberdeen Group, 2015b) it is mentioned that some companies have begun to collect the knowledge and experience of senior experts and started to implement them into various types of digital support. This might be a valuable resource and an opportunity to increase the confidence of engineering designers and design analysts when performing advanced simulations. This approach is close to the intentions set out for the thesis project, though confined to just covering the meshing activity.

Generic templates for design analysis have been used for many years by design analysts. The normal usage of templates is confined to limited tasks such as creating geometry, defining different types of predefined coordinate systems, increasing functionality by utilizing parameterized components and the handling of program license limitations.

Ansys, in its latest releases, offers a functionality that is described as templates (ANSYS, 2015): *"… modules needed for a specific type of analysis can be chosen from different sub-templates to build up an analysis template"*. In a case study within Ford Motor Company's North America Engine Engineering Organization, an analysis template to accelerate the initial geometry and analysis generation process has been developed (Hardee, 2010), focusing on simplifying and automating task-related analysis connections, boundary conditions and mesh generation. Both in Ansys and in the case from Ford Motor Company, the main focus was on the analysis performed by a design analyst, and these templates only handles information related to design analysis and thus not includes the interactions to engineering design.

3.6 Technology or method development

In the development of a TBDA approach the initial activities carried after the identification of those activities which should be implemented in the approach is in current engineering praxis most often referred to as technology or method development.

Technology or method development is currently used by design analysts when performing design analyses tasks. The guidelines define for example which types of meshing are allowed, which loads and boundary conditions are to be considered, which results are to be extracted and evaluated, etc.

Technology or method development is also important for QA and for ensuring that the engineering designers or design analysts only do what they are allowed to do. The role of QA in design analysis for its integration in the engineering design process is also brought up in the literature (Adams, 2006; Eriksson, M. & Motte, D., 2013a). Technology development or method development is present in several companies and is mentioned in the *NAFEMS Simulation Capability Survey 2013* (Newton, 2013), but only a few papers in this area were found, e.g. (Muzzupappa, Cugini, Barbieri, & Bruno, 2010; Stadler & Hirz, 2013; Johansson, André, & Elgh, 2015).

4 Summary of appended papers

This chapter contains the results of the appended papers to be used in answering the research questions.

4.1 Links between the research questions and the appended papers

In Figure 4.1 an illustration is presented showing the links between the appended papers and the research questions.

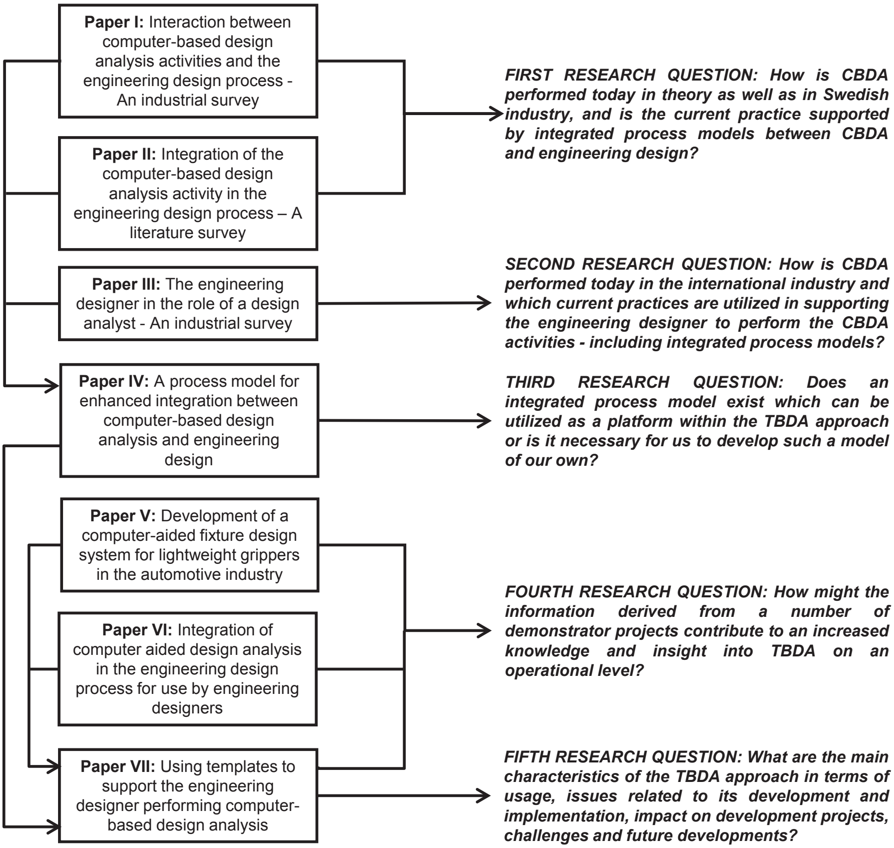

Figure 4.1 Links between the appended papers and the research questions.

4.2 Answering the first research question

How is CBDA performed today in theory as well as in Swedish industry, and is the current practice supported by integrated process models between CBDA and engineering design?

4.2.1 Introductory notes on how to answer the first research question

To be able to answer the first research question, two surveys have been performed; one in Swedish industry and one literature survey. In **Paper I**, the results from the survey in Swedish industry is presented and the results from the literature survey is presented in **Paper II.**

4.2.2 Summary of the results from Paper I

Introductory notes to the paper

In **Paper I** the results from an industrial survey performed in 14 Swedish companies during 2007-2008 is reported for. Three different types of companies were interviewed, companies developing complete technical systems (TS), companies developing complex components (CC) and engineering consulting companies (EC). Table 4.1 specifies the different categories of companies, the sizes of the companies and the main industrial sector in which each of the companies is active.

Table 4.1 Company characteristics.

Category	Size	Main Industrial Sector	Category	Size	Main Industrial Sector
TS	Medium	Equipment for mining and construction	CC	Medium	Transmission components
TS	Large	Mobile phones	CC	Medium	Brake equipment
TS	Large	Water equipment	CC	Medium	Brake equipment
TS	Medium	Power distribution	EC	Small	Software and consulting
TS	Large	Truck	EC	Large	Development, testing and consulting
CC	Large	Transmission components	EC	Small	Consulting
CC	Large	Turbo machinery in aero application	EC	Medium	Consulting

The companies that participated in the survey were all technology-intensive companies in which design analysis was assumed to be of major interest. Their sizes vary from SMEs to large companies. The fourteen companies that agreed to respond to the investigation represent five of each of the first two categories and four of the last category. One EC company approached declined to participate in the survey because it did not want to disclose sensitive information about its process. The responses from the EC companies were in general similar regarding their process, and therefore it was chosen not to pursue any further interview. Nine of the TS and CC companies have product development processes similar to or based on a gate type process, which are available through documents on the intranet. One company has no formalized process but has a number of guiding documents.

General results

CBDA is used for different types of analysis problems and mostly used to fulfill the design specifications when evaluating analysis problems. Planning for the execution of design analysis is done by means of best-practice documents and/or knowledge from the employees. The engineering design department together with the project leader is responsible for the identification and definition of the design analysis to be performed. Design analysis is important for the product development process, especially regarding the evaluation of concept candidates. The companies interviewed have a quite clear view of the importance of design analysis for product development, but it is still viewed as a rather isolated activity. In practice, however, the connection of the design analysis activity to the product development process and available product knowledge at the time of execution is generally loose. The analysis is primarily executed by design analysts as a somewhat isolated task without proper connection to the parallel activities within the project that initiated the design analysis activity.

Methods used in analysis

Most of the companies interviewed have some form of methodology for identifying and defining the design analysis activity, but in some of the companies no formal methodology is present. Instead, the knowledge and experience of the design analyst and engineering designer is the basis for the identification and planning stage. The project leader is often involved in the identification stage, often together with the person responsible for the design analysis and/or engineering design. Execution of the analysis approach and the allocation of resources are primarily based on documented best practices, e.g. guidelines which are based on knowledge gained from previous design analysis activities and knowledge among the experienced employees and departments. When needed, experts from outside the companies are consulted to gain additional insights into the task ahead.

Method or technology development is done in many companies, and it is used for the development and validation of specific guidelines or procedures for the design analyst or the engineering designer to follow when performing a design analysis task. This can be partially or fully automated, and guidelines may be used e.g. to define which meshing types and approaches are allowed, which load and boundary conditions are to be considered, which results are to be extracted and evaluated, etc.

In design analysis, verification is the assessment of the accuracy of the computational model of the design solution; validation is the assessment of the accuracy of the simulation results by comparison with data from reality by experiments (by means of prototypes) or physical measurements in working environments. Only two of the companies have really addressed the verification and validation (V&V) approach of analysis where validated methods are used for verification. The general approach among the other companies is to use a design analyst or a team of analysts and engineering designers, to review the analysis results and thus verify the results. In some of the companies, hand calculations are utilized as part of the verification. Most companies, however, address validation of the analysis by utilizing physical tests. Furthermore, eight of the companies say that they rely on analysis as validation when other means of validation are not available.

CBDA and the engineering designer

Five companies claim that design analysis is performed by engineering designers with the help of a design analyst acting as supervisor and present at least during the reviewing of the result but often also as support throughout the analysis activities. As mentioned above, guidelines are used as support for the engineering designer while performing design analysis, describing how important features are to be performed. They may also be a valuable aid in the planning of employee education (at six companies). This allows engineering designers to perform some specific types of analysis while leaving more advanced analyses to the expert. Experiences from some companies indicate that leaving design analysis to the engineering designer has known pros and cons; but the use of method development is a very controlled way for the engineering designer to do design analysis.

The results from the interviews show that an operational process model for a better integration of the design analysis activities in the engineering design process is needed.

4.2.3 Summary of the results from Paper II

Introductory notes to the paper

In **Paper II**, the results from an extensive literature survey is reported. The survey shows that research on the integration of engineering design and design analysis at the process level is rare. Information about such integration has been found, most frequently in the design analysis books, but no process models on an operational level were found. Both monographs (handbooks and textbooks) and publications from the engineering design and design analysis literature (papers/articles) have been reviewed, followed by the literature on concurrent engineering as well as conferences and journals central to both fields.

General results

There are very few cross-references between research groups and many stand-alone works. Literature from Germany and partly Japan are the only kind with some continuity. Although several case studies reported that this aspect is important, it is largely ignored in the mainstream literature (engineering design textbooks and handbooks). Some recommendations have been extracted from the survey:

- Make the design analysis activity part of the engineering design process and train the engineering designer in design analysis.
- Limit design analysis performed by engineering designers to well formulated and delimited routine and basic design analysis tasks.
- Design analysis can be used for guidance, exploration and optimization, and not only for the specific product-to-be (e.g. material research).
- Increase communication between the engineering designer and the analyst, especially during planning, so that the “right” design analysis problem is solved.
- Enhance coupling between design analysis, engineering design and quality assurance.

4.2.4 Concluding remarks to the answer of the first research question

In five of the 14 companies (35%), engineering designers were active in CBDA. It is interesting to compare this result with the result from the international survey, presented in **Paper III**, in which also 35% were active within CBDA. This, to some extent, validates the results obtained from the Swedish survey. The predominant support was provided by means of guidelines and an active support and supervision by design analysts. In the companies CBDA was regarded as an isolated activity without any connections to engineering design. Neither was he support provided by an integrated process model between CBDA and engineering design found. This concludes the answer to the first research question.

4.3 Answering the second research question

How is CBDA performed today in the international industry and which current practices are utilized in supporting the engineering designer to perform the CBDA activities - including integrated process models?

4.3.1 Introductory notes on how to answer the second research question

Also for this research question a survey was used, but this time in international industry. An on-line technique was used in combination with the support of engineering organizations as ASME, Design Society, LinkedIn and NAFEMS. The support given by these organizations was to introduce and promote the survey and thus supply the necessary respondents willing to participate in the survey. The survey is fully accounted for in **Paper III.**

4.3.2 Summary of the results from Paper III

Introductory notes to the paper

In addition to the perspective utilized in the survey in Swedish industry, this survey focused on the engineering designer in the role as design analyst, thus broadening the perspective on CBDA. The survey consisted of 73 questions about to what extent engineering designers perform CBDA in the companies. Secondly, it is also interesting to" verify", or at least to compare, the results obtained with those from the Swedish survey and the extensive literature survey; especially if integrated CBDA engineering design process models are utilized and open to study. Thirdly, it was necessary to study whether any support is available to the engineering designer performing CBDA, and, if so, what type of support. The survey was answered by a total of 77 respondents in 71 countries around the world during October-December, 2014.

General results

The classification of the different industrial branches originates from the software manufacturer Dassault Systèmes (Dassault Systèmes, 2014). It is similar to the classification used in the NAFEMS Simulation Capability Survey 2013 (Newton, 2013). Industrial equipment (31%), aerospace and defence (23%), and transportation (23%) are the branches in which most respondents operate - see Figure 4.2. They also represent branches where design analysis is often used.

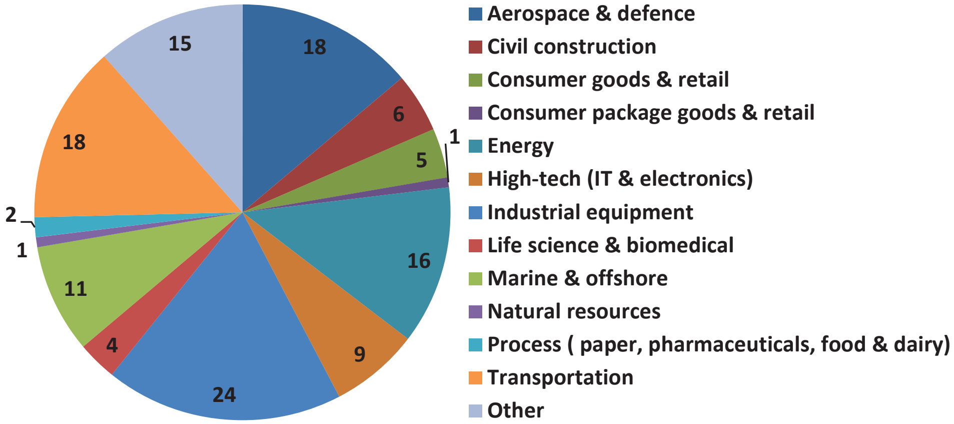

Figure 4.2 Industrial branch to which the respondent's company belongs.

The software used for creating geometry is presented in Figure 4.3. The software most frequently used was Autodesk (36%) followed by SolidWorks (34%) and Catia (30%). Additional software used was NX (21%), Pro/E, Creo (13%), and other (18%). In the Other category the respondents listed special software used for advanced surface creation and other software not listed as a special category in this survey. Least used software is Solid Edge (8%), DesignModeler (4%) and SpaceClaim (1%).

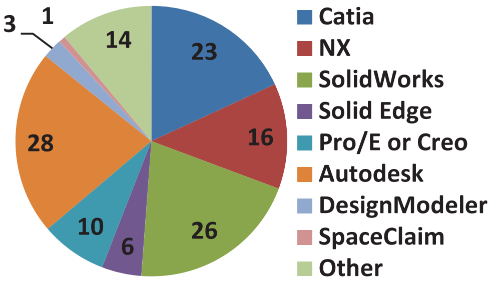

Figure 4.3 CAD software used in the companies.

The majority of the respondents answered that they utilize a formal engineering design process model (44%), see Figure 4.4, but 27% were using a formal CBDA process model, see Figure 4.5. When it comes to fully integrated process models, Figure 4.6, 21% answered that they use an integrated process model. A large number of respondents (37) answered the question with N/A. This might indicate that they either did not know whether their company had any integrated process model or that they did not understand the meaning of the concept of integration in the given context. By cross-tabulating the data, it could be found that of the 27 respondents who answered that they utilize an integrated process, 10 of them involve their engineering designers to perform design analysis.

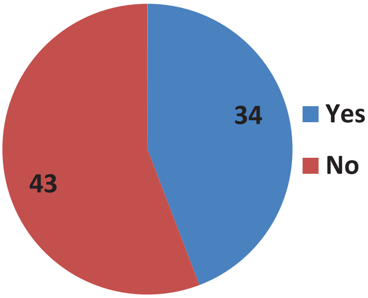

Figure 4.4 A formal engineering design process model is utilized.

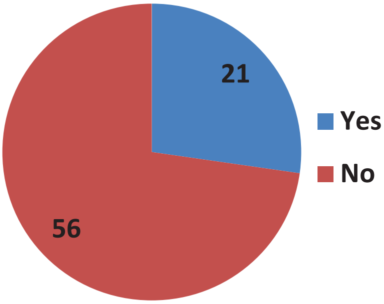

Figure 4.5 A formal CBDA process model is utilized.

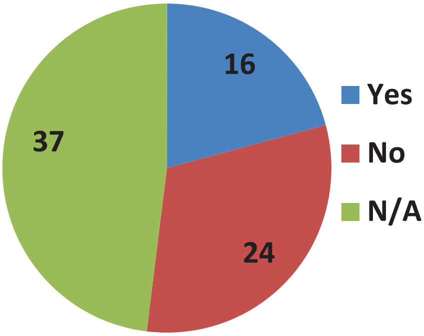

Figure 4.6 The engineering design process model and the CBDA process model are integrated.

Figure 4.7 shows the percentage of the design analysis activities the companies perform in all the different phases of the product development process. The average results, in percentage of the design analysis activities the companies perform in all the different phases of the development process, are presented in Figure 4.8. In this they are compared to the *NAFEMS Simulation Capability Survey 2013* (Newton, 2013). The results are quite similar and indicate that the companies that answered the present survey are representative. The relatively large usage of CBDA in the manufacturing phase can be explained by the fact that the manufacturing of production equipment is a part of this phase.

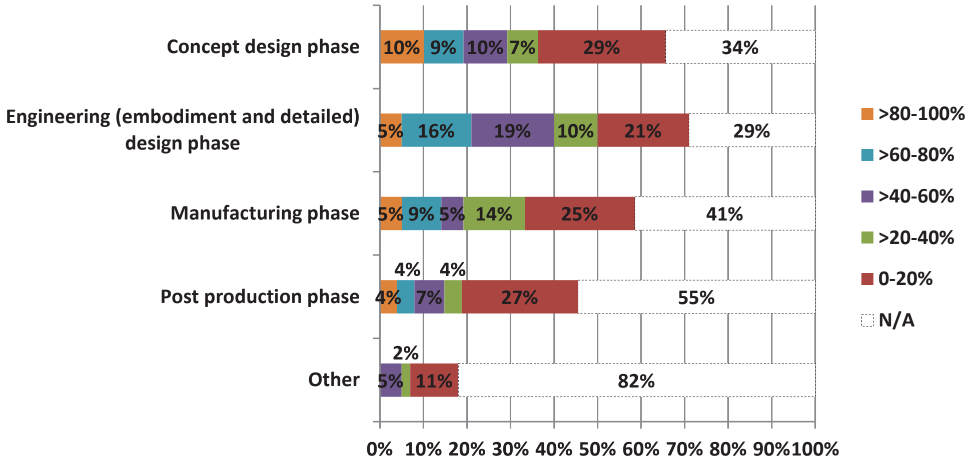

Figure 4.7 Distribution of the analyses performed over all development phases (read: 10% of the companies spent 80 to 100% of their analysis capabilities in the conceptual design phase).

In the *Other* category, respondents have put elements such as analysis for solving problems outside a product development project and failure analysis of returned parts and for analyzing deviations, while in (Newton, 2013) the Other category was primarily chosen by respondents who were using the capabilities for methods development or other research activities.

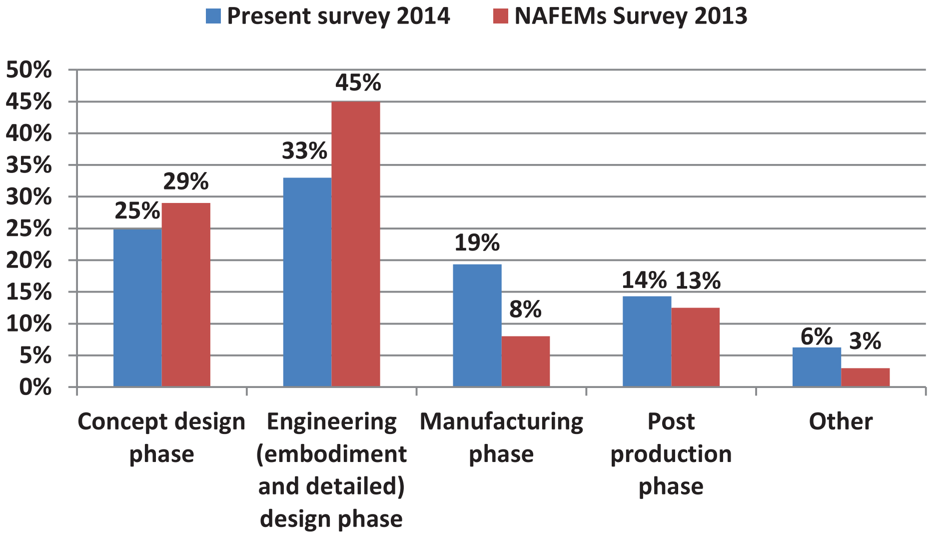

Figure 4.8 Comparison of the present survey with the *NAFEMS Simulation Capability Survey 2013* (Newton, 2013).

The majority of the respondents answered that they utilize a formal engineering design process model (44%), and 27% were using a formal CBDA process model. When it comes to fully integrated process models, 21% answered that they use an integrated CBDA process model - neither presented nor made available for a closer study by us. This validates, too some extent, the value of the answers obtained in the industrial survey in **Paper I** - even though it was made as early as in 2008.

Around 35% answered that within their companies CBDA is used by engineering designers, and 28% of those who are not currently doing so expect to do so in the future. By introducing CBDA for the engineering designers some advantages can be obtained: to allow early evaluation of concept candidates, to free resources for the analysis department, to shorten lead time, to facilitate an evaluation of additional concept candidates, and to facilitate a more extensive generation of concept candidates. This indicates that introducing CBDA for engineering designers is positive. The companies that allow the engineering designers to perform CBDA have a plan for supporting and training them. Supervision by a design analyst (56%), special training (48%) and the use of templates (17%), see Figure 4.9, are the most frequently used kinds of support. The low number for templates (17%) can be explained by the fact that many companies have not yet implemented TBDA.

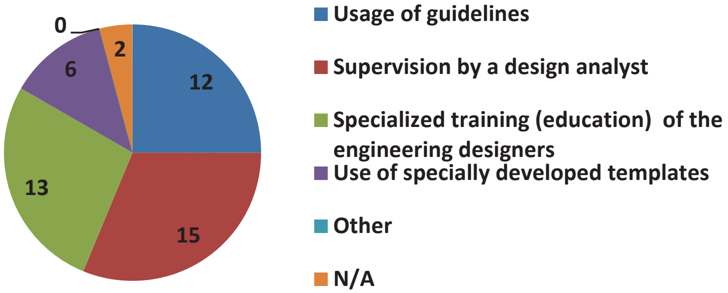

Figure 4.9 Types of CBDA support for the engineering designers.

The development of tools and methods to be used by the engineering designers as well as instructions and training of the engineering designers, are developed in cooperation between the two different departments. One positive side-effect of this cooperation is the increased collaboration between the two departments. Among the different targeted analysis types for which CBDA support for engineering designers has been developed, linear static (85%) is the most frequent one, followed by non-linear analysis (52%). CFD (41%), thermal (37%), dynamic (37%), and optimization (33%) also have CBDA support for engineering designers. Even though the engineering designer performs CBDA on his/her own some type of support is needed for the QA. Most of the companies have some sort of QA approach: control by a design analyst (59%), followed by specialized guidelines (37%) and templates used by design analysts (9%), see Figure 4.10.

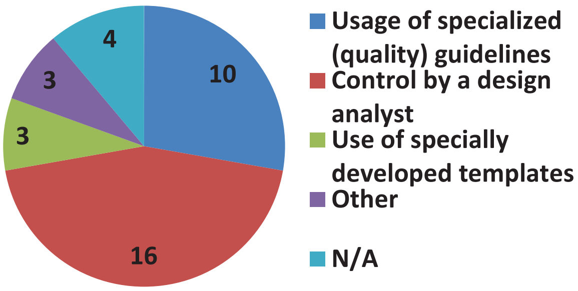

Figure 4.10 Quality assurance for the results of CBDA performed by the engineering designers.

In Figure 4.11 the usage of different types of support along the development lifecycle of a product is shown. All types of support are most frequently used in concept and detailed phases. The use of guidelines and supervision by a design analyst are the types of support used most often.

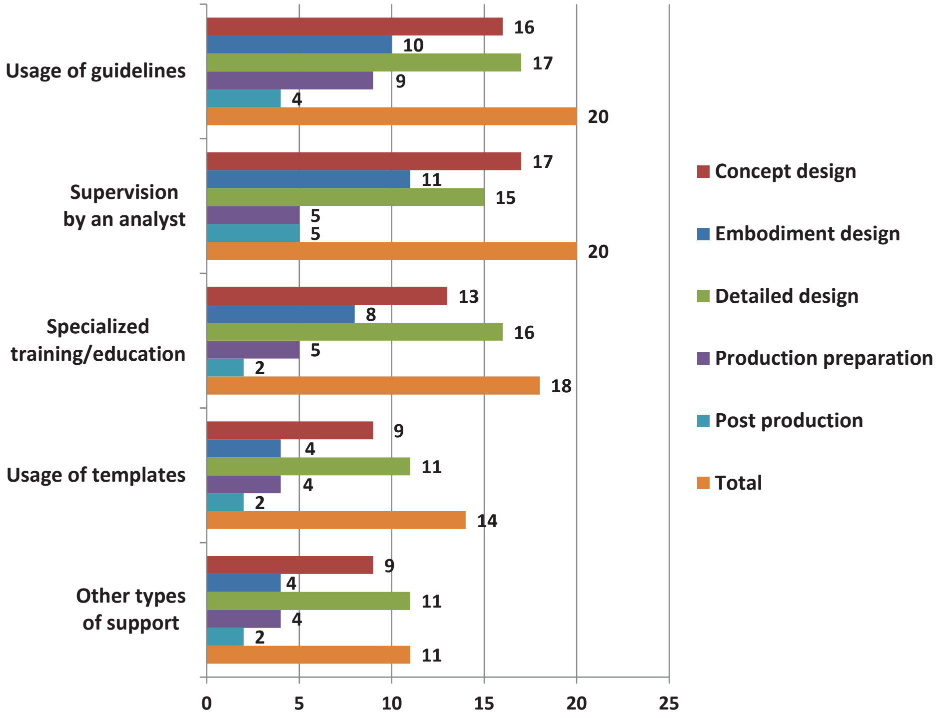

Figure 4.11 Types of support used in the development phase.

Last but not least, the respondents were asked how the company and the users value the different forms of support. In both cases the use of templates gets the lowest score. This can be explained by the fact that it is a less proven type of support, but the companies interviewed were very positive towards templates, and no other explanation could be found. Some speculations as to why this is the case are presented in the conclusion to chapter 5.

4.3.3 Concluding remarks to the answer of the second research question

In 35% of the companies participating in the survey, engineering designers performed CBDA. The different types of support provided for the engineering designers are: usage of guidelines, supervision by a design analyst, specialized training and education, usage of templates and other types of support. Unfortunately, no clarifications were made as to what is meant by other types of support. Some companies claimed that they were using integrated process models, but did not provide any of these models to be investigated by us. This concludes the answer to the second research question.

4.4 Answering the third research question

Does an integrated process model exist which can be utilized as a platform within the TBDA approach or is it necessary for us to develop such a model of our own?

4.4.1 Introductory notes on the answer to the third research question

The results from three different papers, **Paper I**, **Paper II** and **Paper III**, clearly indicated that no integrated process model for the integration between CBDA and engineering design was found in the literature or in the surveys in industry. In the cases, where industry referred to such models, it was not possible to get access to them even for an investigation and thus not to use them directly or as a theoretical platform process for further development. The only available alternative, therefore, was to develop such a process model of our own.

Resulting from synthesis processes based on the findings from the surveys and the authors' experiences gained from design analysis projects in industrial practice, the Generic Design Analysis (GDA) process model was developed. The application of the GDA process model is demonstrated in four examples, which have been utilized for validation of the process model. In one of these examples the development of the TBDA approach for the design analysis of the exhaust valve seating design is presented.

4.4.2 Summary of some of the underlying elements in the development of the GDA process model in Paper IV

The applicability of the GDA process model is to be independent of the engineering design process model, design methods, design techniques and design tools utilized during the development of the design solution to be analyzed. In order to achieve this adaptability of the process model, the constitutive elements of the analysis process, its phases and their corresponding activities must be of a generic nature. Generic, in the given context, alludes to the adaptability of the process model to fit all analysis tasks derived at all levels of concretization of the product-to-be throughout the entire engineering design process and thus also to the overall development processes.

It is important to recognize that the GDA process model primarily provides a sequence of activities to be followed in order to carry out an analysis task in terms of "what to do" and "in which order", but offers very little if any support on "how to do it". In order to be able to answer the question "how to do it", the first step to be taken is to provide a number of core sub activities for each of the constitutive activities of each of the phases, which articulates the contents of each of the activities. This is not enough however, as a detailed insight into all aspects associated with the execution of a specific analysis task is required for the selection of a set of methods, techniques and tools on an operational level, necessary to successfully achieve the goal(s) established for the analysis task in question. Such an insight is only achievable by also considering the influence of the endogenous as well as the exogenous factors. Utilizing these factors, unique to a specific industrial company/enterprise, its environment and the actual design analysis task, provides a detailed and adapted approach to the design analysis task or project at hand.

In parallel with the development of the process model, a research project was carried out aiming at identifying factors that are exogenous to the design analysis process as such but have an important effect on it. In (Eriksson, M. & Motte, D., 2013b) the project and the results obtained are presented in some detail. Also for this project, the findings from the survey in industry **Paper I** together with the results obtained from the literature survey **Paper II** were the main sources of information. Factors are grouped along their levels of influence on the design analysis task; some appear at the basic level of the design analysis and are referred to as endogenous factors, while others appear within the development project, or at the enterprise level, and some outside the sphere of the enterprise, and these are referred to as exogenous factors. The factors elicited in Figure 4.12 are those that have been deemed to have the most influence on the design analysis process.

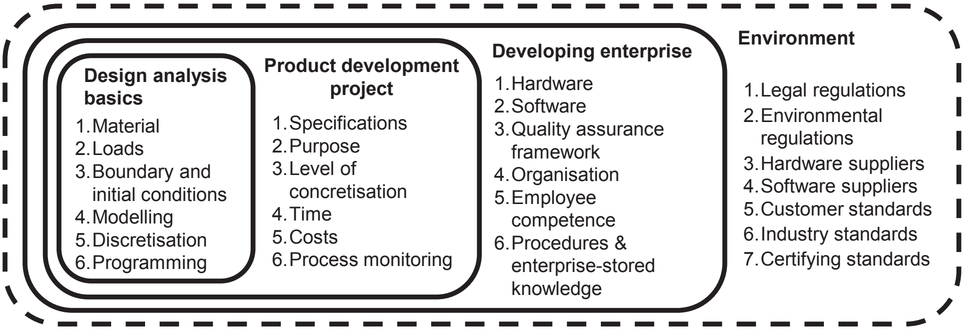

Figure 4.12 Factors influencing the design analysis process (Eriksson, M. & Motte, D., 2013b).

4.4.3 Briefly on the GDA process model from Paper IV

The first version of the GDA process model is illustrated in Figure 4.6. As the adaptation of the GDA process model to a specific design analysis task in industrial practice also requires the “support” given by the factors previously described. The factor model is also included in Figure 4.13. Note that in the factor model, factors in category A are of an endogenous nature, while the remainder of the factors are of an exogenous nature.

4.4.4 Summary of the application of the GDA process model in the TBDA method development project presented in Paper IV

The GDA process model is here utilized for the development of the TBDA approach, including tools, utilized in analyzing exhausts valve and its seating by an engineering designer. The application belongs to the type of method development applications for which the GDA process model is especially useful.

Development of the TBDA approach and tools generates high development costs, but as such an approach can be used for a number of different sizes of combustion engines, that cost seems acceptable. When the company chooses to start method development for a specific type of task, there is, in most cases, a dedicated person or group at the enterprise level that is responsible for the method development and implementation/training provided to their engineering designers. This group also discusses with the design analysis department and/or the person responsible for that department in what project or for which product the approach is to be used **Paper VII**.

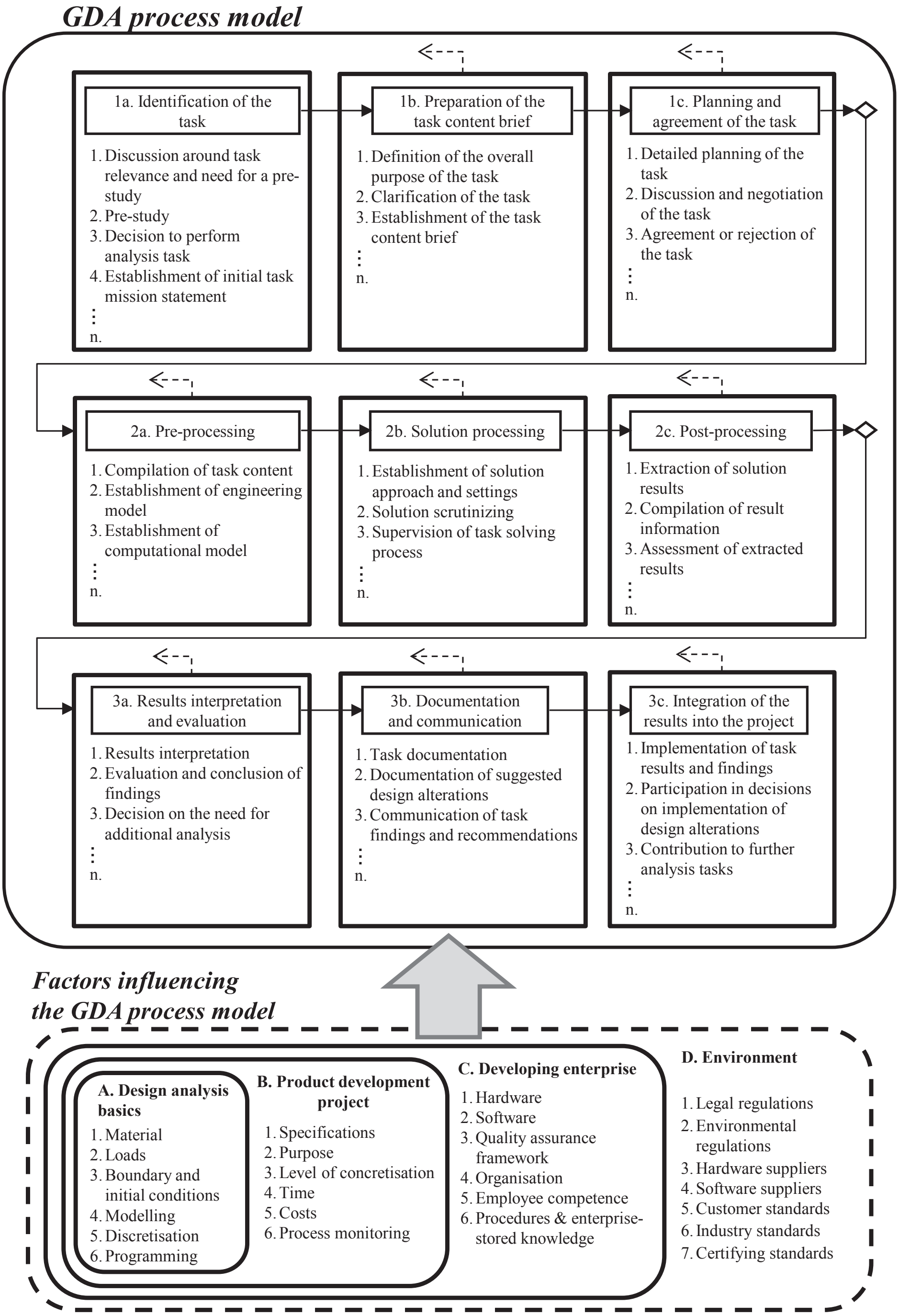

Figure 4.13 The GDA process model and factors influencing it.

By utilizing a simple notation system in the GDA process, it is possible to establish the workflow by combining all of the activities identified as being of relevance for the method development of the TBDA approach. An account of the method development process which concerns us here is presented through the workflow in Figure 4.14. Note that the factors previously referred to are not accounted for in this project, as they contain information of a proprietary nature not to be revealed.

Project planning (PP) process is the starting point were the relevance for this type of method development is discussed and agreed upon. It is followed by a pre-study to evaluate if the project is suitable and if a method should be developed for this type of design task (conceptual studies of exhaust valve and seating designs, 1-4). One important issue is the quality aspect of the template approach and how to ensure that the users can only do things that they are allowed to do. It was decided during the definition of the overall purpose of the task (5) that the implementation of KBE in the developed template should provide the quality assurance needed. A special user interface to support the engineering designer who does not possess the adequate knowledge of design analysis was developed by using Visual Basic programming. The computational model is developed, a basic setting for the analysis is applied and parameters are connected to the geometric model. Note that during this activity the method development involves a number of analyses in order to fully manage all possible solution outcomes. When developing new methods, especially if they are going to be used by less experienced engineering designers, it is important that the solving process during solution processing (11) does not exceed the solving time and problem size planned for the task. Supervision of the solving process and evaluation of the computational model for inconsistencies and other unexpected issues that may arise during the solving process are necessary.

Under the extraction of the solution results (12), “sensors” (extreme values in form of parameters) and predefined plots are implemented. The sensors are also utilized for assuring the quality, by comparing the result with the agreed settings for the specific task. If any values are outside the valid range, warnings appear, informing the user that the given solution is not valid. With this type of method development, consistency of both the geometrical and the computational model is important. A number of different computations are performed for verification of the template developed (13). During the same phase an extra validation is performed with external analysis software. After the validation has been completed, task documentation (14) is made, containing the full process of the method development as well as the background information on its purpose. As the developed template is meant to be used by different users, a user guide (15) is written to support the engineering designer while performing analysis by using the template. The last sub activity in the method development is finalizing the method development (16) and implementing the template (17) for use in the engineering design process.

GDA process for method development

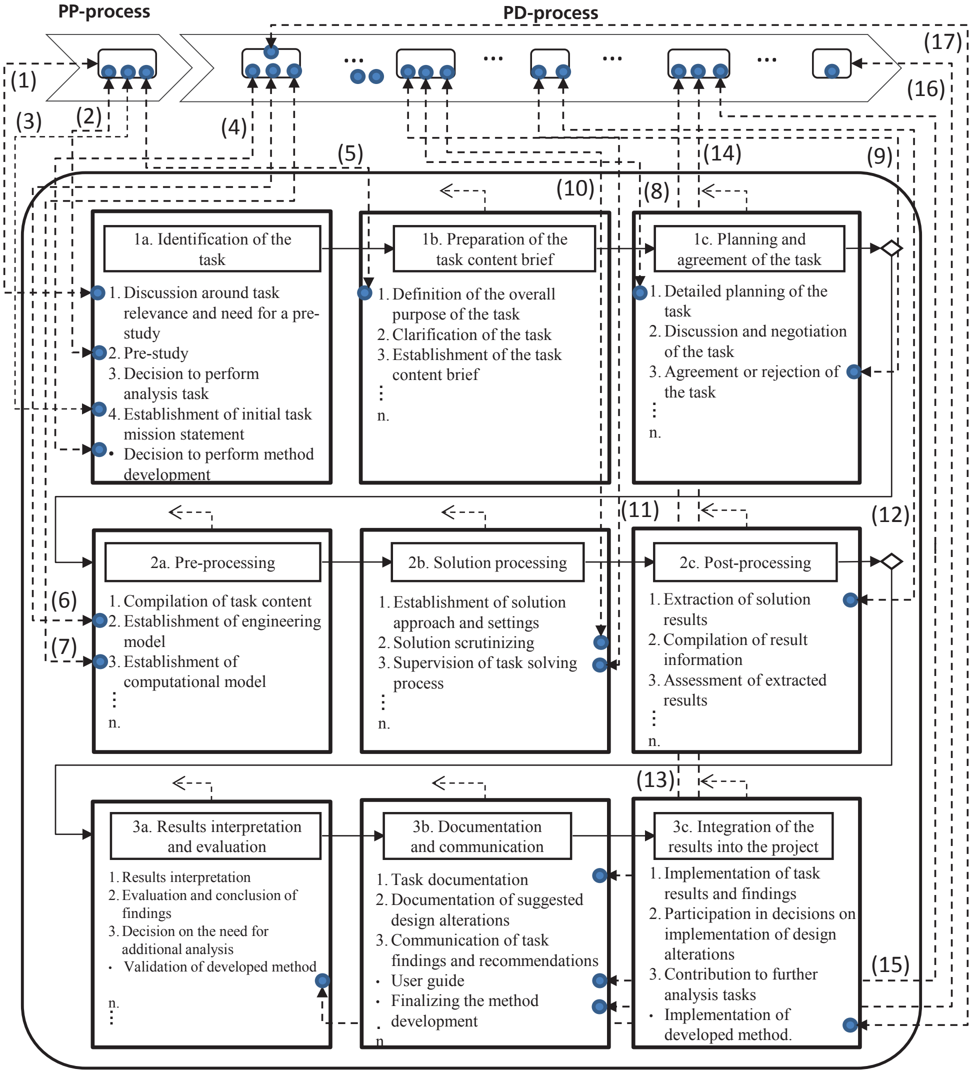

Figure 4.14. Workflow of the method development of the TBDA approach for the design analysis of exhaust valve seating. The notation PP refers to the Product Planning process and PD to the Product Development process.

4.4.5 Concluding remarks to the answer of the third research question

From the results obtained in **Paper I**, **Paper II** and **Paper III**, it was clear that no integrated process model for the integration between CBDA and engineering design was found either in the literature or in the surveys in industry. This resulted in the development of the GDA process model. This concludes the answer to the third research question.

4.5 Answering the fourth research question

How might the information derived from a number of demonstrator projects contribute to an increased knowledge and insight into TBDA on an operational level?

4.5.1 Introductory notes on how to answer the fourth research question

This research question is answered by the contents presented in partly in **Paper IV, Paper V, Paper VI** and in **Paper VII**. The answer to this research question is derived from the results obtained from these four industrial TBDA cases performed in close cooperation with industry.

4.5.2 Summary of the results from Paper V and partly Paper IV

In the paper, the development of a computer-based design system for lightweight grippers was developed. The design system was intended to be used by production engineers during the complete development process. As the production engineer traditionally does not possess knowledge within engineering design nor in CBDA, an automated computer-based design system had to be developed. In this paper the full process of the development of the design system is reported as well as its architecture, based on KBE, and the CBDA activities utilized in the design system. Even though this paper had a different focus from the beginning, i.e. the development of a computer-based design system for lightweight grippers and fixtures (Computer-Aided Fixture Design System (CAFDS)), it can be seen as the first version of a TBDA approach.

As production engineers are the targeted users of the design system, restrictions have been made regarding their role as “engineering designers”. One such restriction is associated with the generation of conceptual solutions and evaluations of them for a specific product – here referred to as a Body-In-White (BIW). By utilizing predefined concepts for the lightweight gripper base, it is possible to avoid major problems during concept development and design, thus reducing the concept generation to more or less a simplified adaptation of the gripper base alternatives found in the concept library. Two examples of such gripper base alternatives are given in Figure 4.15. The gripper, in the prototype production cell, was previously presented in Figure 1.1, section 1.1.

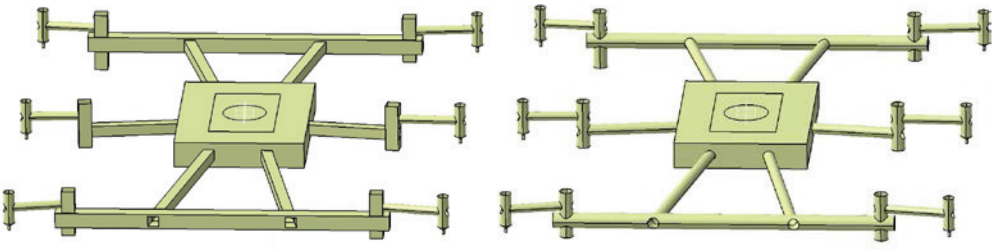

Figure 4.15 Possible configurations of the gripper base (Petersson et al., 2012).

The templates utilized in the design system provide a fully automated computer based design system. It is developed so that the user's handling of the templates is simple and reduced to minimum. When the user starts up the system in the first stage, the only interaction needed is the creation of a small number of reference points, one at the center of each reference hole on the BIW product. The reference points are then connected (which can be done automatically by using Visual Basic) to the gripper geometry within the TBDA. When the BIW geometry is connected to the TBDA, parameters have to be checked and compared with target values for the specific prerequisites and, if needed, the values changed. The procedure can be started and it runs until the target values have been reached. After completing the search for an optimal solution, the user can search for alternative solutions from the data generated during the search for a solution. If the BIW is updated, the gripper solution needs to be updated, too, and this is done by restarting the procedure. The BIW can also be replaced as long as the reference points on the replacing BIW are named in the same way as the replaced BIW.

The computer-based design system has been verified as a fully working digital prototype for a number of different BIW geometries.

4.5.3 Summary of the results from Paper V and partly from Paper VI

In the paper, a different automation level of the TBDA is reported. The object of this TBDA project was an exhaust valve and it’s seating for a truck engine, see Figure 4.16. Results of interest were stresses, deformations and the optimized angle between the valve and the seating. The industrial project was set up with two different goals. The first one was whether or not it was possible to utilize TBDA in a way which made the user more involved in the actual CBDA activities. The second one was to see whether it was possible to integrate Abaqus for Catia (AFC, a plug-in for Catia V5) into the TBDA in terms of capabilities and handling as well as in terms of integration with other Catia V5 workbenches, for example KBE and the Product Engineering Optimizer (PEO). AFC has more functionality than the standard CAD integrated FEM workbench, Generative Structural Analysis (GSA), as the company was planning to start using enhanced capabilities, e.g. non-linear and contact conditions.

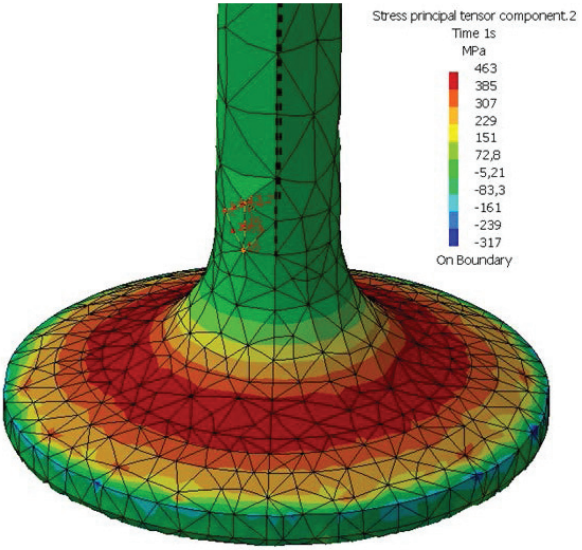

Figure 4.16 Stress distributions in the exhaust valve Paper VI.

The fulfillment of the first goal was an enhanced number of generated concepts, increased knowledge about the product and of the engineering designer, and a considerably improved collaboration between the engineering design and the design analysis departments.

For the second goal, validation of the implementation of AFC compared with GSA, the result was both positive and negative. There are some limitations when integrating AFC with the TBDA, but most of these could be solved by using a different approach. Feedback from the company was positive and they are planning to use both GPS/GAS and AFC for their engineering designers, depending on their skill and what type of analysis to be solved.

The industrial case study in **Paper IV** was based on the exhaust valve project accounted for above. In the project it is demonstrated how the actual activities between CBDA and engineering design were identified and utilized for the development of the TBDA approach as well as the templates and additional tools, KBE support etc.

The additional TBDA demonstrator projects presented in **Paper VII** are the design of a crankshaft and of a sheet metal bracket. They are presented in some detail in section 4.6.2 and will not be commented upon here.

4.5.4 Concluding remarks to the answer of the forth research question

The results obtained from the demonstrator projects are based on **Papers IV, V, VI** and **VII**. The development of the computer-based design system and the exhaust valve represent the first versions of operational TBDA approaches to be used in industrial practice, with two different automation levels. Here follows a short summary of results obtained from these and from the other industrial demonstrator projects:

- The introduction of templates including KBE support, developed by design experts and/or design analysts during a method/technology development process has proven to be a successful concept for facilitating the development of templates for non-expert design analysts.
- The designer can perform evaluation of a concept or a detail early on in a conceptual design phase and will thus be able to eliminate a large number of candidates without the involvement of the analysis department; the work can be focused on the concepts/details in question, resulting in a deeper understanding of the technical realities and thus in an increased product quality.
- The lead time for developing new products has been significantly shortened as the engineering designer can perform design analysis directly when needed. For some other projects, the lead time has not decreased, but the quality of the design has increased.
- The extensive use of templates makes it possible to monitor and secure the quality of the design analysis project. The engineering designers' knowledge of analysis may be limited, but by introducing TBDA it prevents the engineering designer from making mistakes.

The designer may, in some cases, need the assistance of an expert design analyst when analyses are carried out, when results are interpreted and when unexpected difficulties occur during the design analysis. This concludes the answer to the fourth research question.

4.6 Answering the fifth research question

What are the main characteristics of the TBDA approach in terms of usage, issues related to its development and implementation, impact on development projects, challenges and future developments?

4.6.1 Introductory notes on how to answer the fifth research question

The research question is answered by the results provided in **Paper VII**. In that paper, three TBDA demonstrator projects are presented together with the results obtained from a follow-up of the on-line survey in the form of interviews of five Swedish companies which were selected on the basis of their current use of TBDA or for their intentions to introduce TBDA in a near future. The results presented in the paper provide the current status of the TBDA approach expressed in terms of basic characteristics of TBDA such as: 1) The usage of TBDA, i.e. the different types of templates used on an operational level supporting a functionality which ranges from basic to fully automated, the different types of analysis performed with templates and exemplified with demonstrator projects in industry, and the implementation of TBDA in the development process; 2) issues related to the development and implementation of templates, and the knowledge and training required of the engineering designers; 3) impact of the use of TBDA on development projects; 4) challenges and future developments. Each of these are accounted for below.

4.6.2 Summary of the results from Paper VII

Regarding the use of TBDA

Three different automation levels of TBDA have been identified (from fully automated to basic) and accounted for as well as exemplified. The differences between the levels are as follows. How many KBE functions have been implemented, what type of analysis could be performed and to what extent was the user able to work singlehandedly. The last question is dependent on the engineering designer's knowledge of CBDA. The different templates utilized on the three levels of automation are illustrated by three demonstrator projects. The first one concerns the templates utilized for the lightweight robot gripper (fully automated template), the second one a template for the optimization of a crankshaft (semi-automated level template) - see Figure 4.17 (Upper), and the third one finally the type of templates utilized on a basic automated level for the optimization of a new sheet metal bracket - see Figure 4.17 (Lower). By using TBDA for the optimization of the crankshaft and for the sheet metal bracket, deeper insights into the actual designs were obtained. Regarding the crankshaft, a large number of concept candidates could be designed and evaluated, and as for the bracket a weight reduction of 80% was achieved with the new design. A significant reduction of lead time was also achieved. - from 12 months to 2 months. This had not been possible without access to TBDA, since the design process required a number of redesigns and corresponding analyses and optimizations. In the traditional setting, this required a great deal of interaction between the engineering designer and design analysts, whereas now the engineering designer could perform the entire process on his/her own.

As this was a demonstrator project, a design analyst supervised the users during the project but did not interfere in the actual work. The project also resulted in the development of new guidelines to be used in combination with TBDA. The guidelines were intended for future use by the design analyst and engineering designer with knowledge and experience of CBDA.

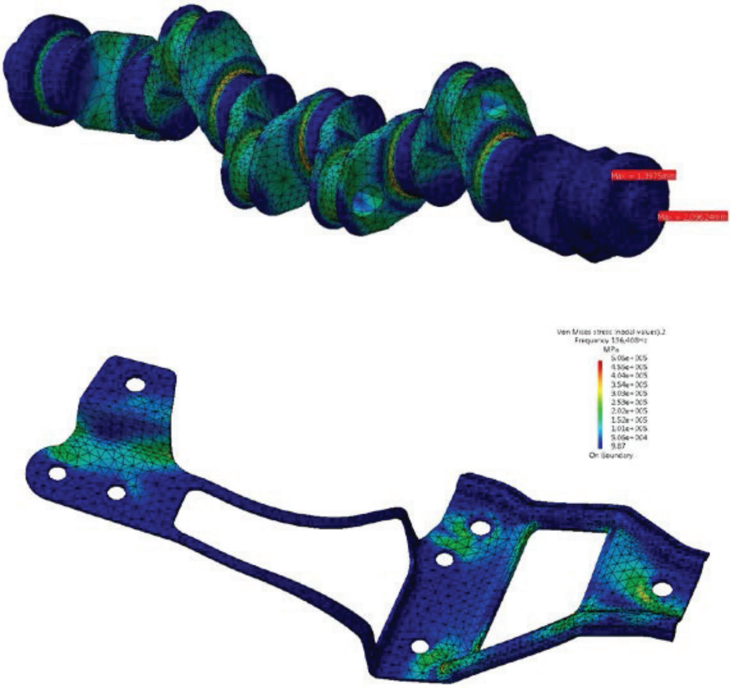

Figure 4.17 Upper: Optimization of a crank shaft. Lower: Optimization of a sheet metal bracket – both accounted for in Paper VII.

In Figure 4.18 the usage of different types of analyses is related to the actual automation level used. Note that many companies use several types of templates.

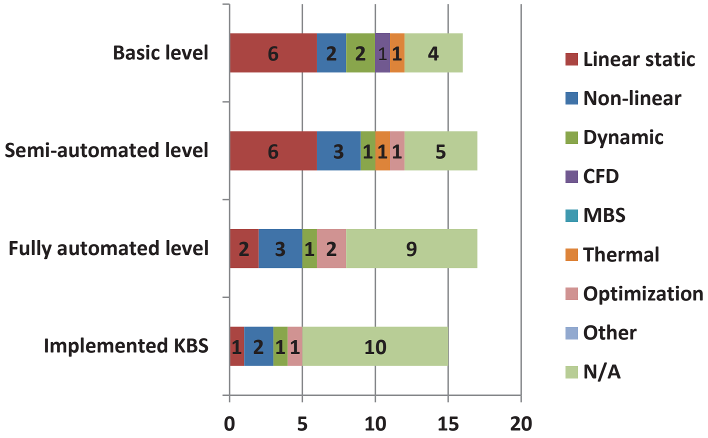

Figure 4.18 Types of analysis for different levels of TBDA.

Regarding implementation of the templates in industry, the companies interviewed stated that they are in the early stages of their implementation of TBDA. Many of their TBDA projects served to test whether templates actually helped engineering designers perform CBDA and increased product quality. The majority of these projects were performed for real products or parts, and their solutions have been implemented. Even though TBDA is in the early stage of development and implementation, interesting results are reported – see Figure 4.19.

During the interviews, the respondents answered that they have noted increased lead times in a number of concept generations projects, which on the other hand have resulted in increased knowledge about the product and ultimately improved quality of the final product.

Regarding development and implementation of TBDA

Time and costs are critical for an extended implementation of TBDA. From the interviews it is clear that not all of the companies possess the required knowledge for developing more advanced levels of TBDA. One solution could be to start collaboration with an academic institution, which could also result in more extensive cooperation between academia and industry.

It is also interesting to notice that, for most companies interviewed, there is a dedicated person or group at the company level that is responsible for both the TBDA implementation and the training/education provided for their engineering designers. This person or group also discusses with the design analysis department and/or the person responsible for that department in what project or for which product TBDA is to be used. Another important factor is the total cost of developing TBDA. Licenses, adaptation of software, implementation of TBDA and any education/training of engineers are all factors that must be taken into account when evaluating the benefits of TBDA obtained.

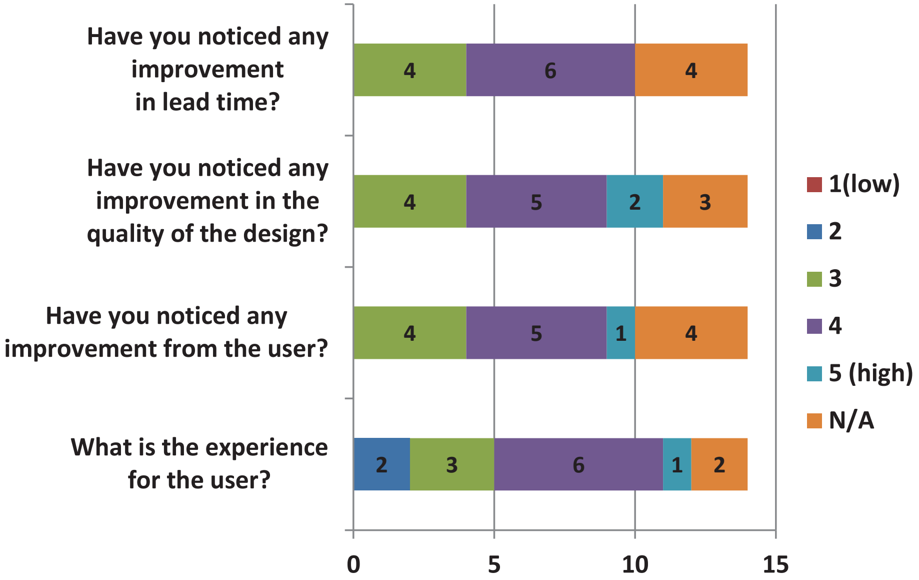

Figure 4.19 Experienced improvements through TBDA.

Regarding training and knowledge pre-requisites for the engineering designer, according to the survey, engineering designers leaving university are not skilled enough in design analysis. It is therefore of vital importance to give them proper training/education before they start using TBDA. Some of the companies are now in the process of developing a new type of education/training that directly focuses on TBDA and CBDA; some of them have already established an internal training program.

Regarding the impact of the use of TBDA for engineering designers and for companies

As TBDA is a new type of support, experiences are still few and far between. In some companies, as mentioned earlier, demonstrator projects with TBDA have started. In some of these, real products have been developed to be used commercially; for these the basic level approach has mainly been utilized. Education of the engineering designers and the usage of TBDA have proved to have a positive effect on the whole company, as the collaboration between the engineers and design analysts and other categories of the staff is increasing.

One result from the increased generating of more concept candidates is that the engineering designer has gained a better technical understanding of the products resulting in a higher quality of the product; see Figure 4.19. This also results in an increase of the engineering designer's understanding of and insights into CBDA. As a result of these improvements, the analysis tasks (primarily digital product models) sent to the analysis department have a higher technical maturity, and therefore the analysis department does not need to prepare the analysis models to the same extent as before the introduction of TBDA. The number of iterations between the engineering and analysis departments has increased, which is somewhat surprising. However, this was found to be a result of the engineering designer's higher level of knowledge within CBDA and the higher technical level of the design analysis objects, and both the analysis and the products have attained a higher level of quality. From the design analysis point of view, TBDA is an important support tool and in some companies there are forces pushing for an extended implementation of TBDA as soon as possible.

From the company's point of view, it is clear that by introducing TBDA some benefits have been reached. Most importantly, it is now possible to develop more concept candidates and to perform more analysis based evaluations of the concepts. Also, the results generated by TBDA have high accuracy; fewer physical tests are required, which means economical savings. Furthermore, one challenge for the company is to be able to motivate and retain their engineering designers. By introducing TBDA, engineering designers have a great opportunity to have their demands for more advanced tasks fulfilled.

Regarding challenges and future developments

All of the companies that have provided information about TBDA are very clear that the implementation is going to continue. Some demonstrator projects have been finished and some ongoing projects are to be evaluated. The highest priority is to cut the lead time for the development of the product, but there is also a demand for lighter products and higher product quality. The main issue now is to review the results from the demonstrator projects, to review all processes involved and to adapt them to a full implementation of TBDA. To be able to handle processes that are affected by the implementation of TBDA, changes have to be made also at the organization level. Also, information received from the companies indicates that they do not have a clear picture of the total costs for developing and implementing TBDA. A practical difficulty that may also limit the implementation and development of TBDA is that it requires software that has features better adapted to the demands from for TBDA. Basic level templates require advanced design analysis tools, and for semi-automated and automated templates KBE and other systems might be required.

The company might need to update its current solutions or change its CAD/CAE systems, which is a question of a strategic nature.

As mentioned before, not all companies plan to implement CDBA, and therefore also not TBDA, for their engineering designers. Some companies do not plan for their engineering designers to perform CBDA in the near future. The reasons for this are that they do not have suitable projects or products, and the costs are considered too high or the return on investment too low. In some companies, it is company policy that the design analysis department should perform and carry responsibility for all CBDA activities within the company. Also legal requirements or other standards may prevent the companies from delegating CBDA to engineering designers.

Finally, in the present survey, 38% of the respondents answered that TBDA has not been implemented yet, which could mean that they are considering it or have started to think about it.

4.6.3 Concluding remarks to the answer of the fifth research question

Answers to each of the four characteristics introduced in the research question are given above. This concludes the answer to the fifth research question.

5 Conclusion, recommendations and further research on TBDA

In this chapter, the answer to the main research question is given, based on the answers to each of the research questions accounted for in chapter 4. This answer is further elaborated upon by adding findings from the interviews in ***Paper VII*** *of the five Swedish companies and the on-line respondents currently using TBDA or planning to do so in the near future. Recommendations for a successful implementation and use of TBDA are discussed next. Finally, research on important issues for further development of TBDA is accounted for.*

5.1 Conclusion

Based on the answers to each of the research questions accounted for in chapter 4, it is possible to give an answer to the main research question:

Does the TBDA approach provide sufficient support to become a competitive approach in industrial design practice in comparison with existing approaches utilized by engineering designers in performing CBDA singlehandedly or in any other organizational setting?

From the answer to the second research question, the following competitive approaches to support the engineering designer during CBDA were found: use of guidelines, supervision by a design analyst, specialized training and education, usage of templates and other types of support.

The support most frequently used by engineering designers and design analysts is guidelines. This type of support is the closest to TBDA as it provides a documented procedure to be followed by the user. Note that this documentation might also be provided in the form of code. Regardless of how the guidelines are presented to the user, it is presumed that the user is able to interpret the contents of the guideline unambiguously and thus avoiding serious mistakes. However, this requires that the user possess such knowledge and insights that it is possible for him/her to singlehandedly handle the information provided by the guidelines. This is definitely not the case for the majority of engineering designer when it comes to performing CBDA.

Since the TBDA approach provides the support necessary to overcome the lack of knowledge and experience of CBDA, this approach is definitely a very competitive alternative to the use of guidelines in these cases. From this aspect, TBDA is more of a complement than a competitor and thus defends its existence as an alternative approach to guidelines.

In industry, supervision is often used to support engineering designers in performing CBDA. This type of approach is very resource demanding unless combined with some other type of support such as specialized training and education, guidelines and even the use of TBDA.

In the discussion above it is assumed that a TBDA approach exists which provides all of the qualities necessary to fulfill its functionality as described. The core activities of the TBDA approach are initially presented in section 1.1 and contains the following activities:

1. Decision on whether or not to develop a TBDA approach, as this presumes a repetitive design analysis process focusing on a specific type of product – ranging from a complete design system, as described above, to the embodiment of a detail in a part of an overall design solution.
2. Identification of those activities from the engineering design as well as from the CBDA processes to be included in the TBDA approach.
3. Development of the actual TBDA approach, including development of the templates and additional tools, by means of method or technology development.
4. Software implementation of the TBDA approach; and training of the users of the TBDA approach.

As descried in chapter 2, an evolutionary approach has been adapted for the development of the TBDA approach. Below, an account of the contributions from the research questions to a deeper understanding of the core activities of the TBDA approach is provided.

Activity 1: In the operational perspective this is performed by utilizing a method development approach such as described in **Paper IV** regarding the design of an exhaust valve and seating. This approach is recommended at the present level of development of the TBDA approach.

Activity 2: For this activity, the GDA process model presented in **Paper IV** is the recommended approach. In some cases, a pre-study of the analysis project might be favorable in the final identification of activities – see **Paper VI.**

Activity 3: When the activities forming the actual TBDA approach are known, it is possible to develop the templates. This is usually a rather complex task and involves both engineering designers and design analysts. Examples of the development and application of templates are found in the demonstrator projects accounted for in **Papers V, VI** and **VII.**

Activity 4: Implementation of the templates into code, including support by KBE decision aid, is presented in **Paper V** and **VI.**

To summarize:

> ***The discussion accounted for above clearly supports the claim that the main research question is fully answered. Furthermore, it is also concluded that the TBDA approach is not only a competitive approach to current alternatives in supporting the engineering designers performing CBDA, but also of a complementary nature providing functionality not included in the alternative approaches currently used in industrial practice.***

In addition to this conclusion, further arguments for the TBDA approach were extracted from the results of the interviews presented in **Paper VII**, as well as from the other surveys in industry and the literature survey. Note that the arguments represent an overall perspective on a managerial level of the current and future development of TBDA. These arguments are presented in the following sections.

5.1.1 Higher effectiveness

TBDA enhances effectiveness in several areas:

- By introducing TBDA, design analysis will have a more central impact during the whole product development process.
- Improved and increased collaboration between the engineering design and the design analysis departments.
- Overall shorter lead times, but the time saved is used to generate more concept candidates and thus contributes to a higher product quality.
- Fewer physical tests are needed, resulting in economical savings.
- By introducing TBDA, the company sets a standard in how CBDA ought to be performed.

- Updating a specific TBDA approach can easily be done through the company's Product Data Management (PDM) system.
- The increased knowledge of CBDA on the part of the engineering designers using TBDA, results in more advanced analysis models provided by engineering designers in the cases where design analysts need to take over the actual design analysis task.
- TBDA can serve as a QA tool.

5.1.2 Enhanced knowledge

TBDA enhances the knowledge level in the company:

- The companies reported that the engineering designer has significantly improved their knowledge of and ability to perform CBDA by using TBDA.
- A deeper knowledge and insights of the product-to-be is obtained and thus of the quality of the final product.
- The design analyst has increased his/her knowledge within engineering design.
- The engineering designer has gained better technical understanding of the technical solution candidates developed.

5.1.3 Positive response of the implementation of TBDA

The positive responses of the implementation of TBDA in a company are:

- Experienced engineering designers are initially negative to the implementation of TBDA due to their experiences of other forms of design analysis. However, in the end the majority were positive since TBDA provides increased opportunities for concept generation and increase in product quality.
- The design analysis department is positive to the implementation of TBDA and it is the individual design analyst who is pushing for the implementation of TBDA.
- Some companies plan to implement TBDA as soon as possible, thus enabling them to introduce new methods to ensure that all analyses are performed according to the same standard.

5.1.4 Challenges and limitations

Even though TBDA supports the engineering designer in his/her role as design analyst, there are some restrictions associated with this implementation:

- Additional advanced software licenses may be needed and are expensive.
- The implementation of TBDA most often requires changes in the organization of the departments of engineering design and design analysis.
- The CAD software used in many companies does not support the implementation of TBDA.
- Users find themselves constrained using TBDA.
- When TBDA is integrated into the product development process, it is important that processes affected by TBDA are adapted to this integration.
- It is important to plan an introduction of TBDA carefully and make sure that the personnel are well informed about what the impact and benefits of this implementation might be.

5.1.5 Possible restrictions for the introduction of TBDA in industrial practice

Information obtained during the surveys indicates that there are many different factors that have to be taken into account when or if TBDA should be implemented.

TBDA specificities limit its use in several contexts:

- Development of TBDA requires special knowledge and skills within CBDA and related processes.
- No suitable product is available when introducing TBDA.
- Some companies will not allow engineering designers to perform CBDA.
- Schedule during the development project is too tight for the development of a suitable TBDA approach.
- Companies are restrictive in introducing new processes and procedures.

5.2 Recommendations

The recommendations accounted for here are primarily intended to pinpoint some of the essential information needed to facilitate a future decision on introducing TBDA in an industrial company.

5.2.1 For the adoption of TBDA

As the development of a TBDA approach for a specific type of product, technical solution or CBDA task requires extensive resources, it is of the utmost importance that the actual resource need is fully addressed. Among the resource needs, the access to competence for developing the TBDA approach is one of the most difficult and expensive. It is preferable to have this competence in-house, but also external competences might be utilized such as consultants and university institutions. The need for additional software licenses and more powerful hardware are also expensive.

In the surveys comments were given about the combination of TBDA and PLM systems. Companies that have evaluated the TBDA concept are pleased with the outcome, but all expressed a concern about the PLM system and their current limitations. One concern is that the PLM systems have to be able to handle large amount of data and a large number of files, generated from the analyses. Different configuration of the data files containing the geometrical information might require sub processes within the PLM system. Another advice is to check if there are other processes and/or software that may affected and are needed to be adapted, before the implementation of TBDA. One solution might be to minimize the number of software from different vendors and to make the platform consolidate (Aberdeen Group, 2015a).

5.2.2 For the development and implementation of TBDA

When implementing TBDA it is essential to set up the goal to be fulfilled and to make a plan for how to implement the approach. For simpler products, technical solutions or CBDA tasks, less functionality is needed, which limits the development time and costs. For cases where frequent use of the approach is expected, e.g. when a large number of concepts are to be generated and evaluated and in some cases also optimized, a completely automated approach is preferred. In other words, the level of automatization and available time are key factors to be considered during development and implementation of TBDA.

5.2.3 For the use of TBDA

TBDA should be easy to use and the user should be well prepared in advance in how to utilize the TBDA approach at hand. From the user's perspective, TBDA requires more efforts on behalf of the user than alternative supports. In order to promote speedy implementation and use of the TBDA approach, the active support on a personal level between the engineering designer and a design analyst might be favorable.

When a specific TBDA approach is fully integrated into the company's PLM system, it is necessary to make sure that the latest version of the approach is utilized. This also assures that the QA routines are followed. In other words, a fully implemented and integrated TBDA approach also contributes to support the engineering designer in his/hers role as a design analyst. Furthermore, by using TBDA, new information and updates are automatically saved in the company's PLM system, enabling the current update to be available worldwide.

5.3 Further research on TBDA

For future research on TBDA, four areas of interest have been identified, namely adaptation to different levels of abstraction of the product-to-be in the engineering design process, full-scale implementation projects, implementation into PLM systems and synthesis oriented TBDA. It is also of interest to further develop the integration of CBDA in engineering design and method development of CBDA, as these areas have an indirect but important impact on the future development of TBDA.

5.3.1 Adaptation to different levels of abstraction within the engineering design process

Developing a TBDA approach of a generic nature, which can be adapted to all levels of abstraction of the product-to-be in terms of reflecting the actual phase within the engineering design process (i.e. concept design, embodiment design and detailed design), might be helpful if we wish to facilitate an efficient and effective utilization of the approach in the future. This indicates that the TBDA approach is transformed from being just an approach to being a well-established process model.

5.3.2 Full-scale implementation projects

In addition to the demonstrator projects accounted for, it is important to study a full-scale implementation of the TBDA approach in some companies. The outcome of such a project would be extremely valuable by providing experiences useful in improving the overall concept of TBDA.

5.3.3 Implementation into PLM systems

The implementation of TBDA into a PLM system needs to be investigated to accommodate the functionality and adaptation expected. Examples of activities for such a study are how to create and configure suitable geometry for the design analysis model, what information (digital files) should be saved in the PLM system, how to save generated data, especially large files, and what processes and/or software, e.g. manufacturing processes and software, could be affected by the implementation.

5.3.4 Synthesis oriented TBDA

In the TBDA approach focus is set on design analysis. As was mentioned regarding the computer-based design system for lightweight grippers, in section 1.1, the synthesis activities were also included. For the future development of the current TBDA approach, studies of the integration of template-based synthesis activities with the current TBDA approach into a *Template-Based Design Synthesis and Analysis*, or TBDSA, might constitute an interesting extension of the original concept.

5.3.5 Integration of CBDA in engineering design

Integration of CBDA into the engineering design process is still an area with little development. Companies reported that their processes are integrated but no one was able to provide such a process model (**Paper I** and **III**). Even in research the information about this integration was very poor. The literature survey **Paper II** showed that integration of design analysis into engineering design methodology is next to inexistent. From the surveys and from the industrial cases it is shown that by letting the engineering designer perform design analysis, many different advantages could be received. To be able to develop this even further, more research should be focusing on integration.

In order to fully utilize the advantages provided by the TBDA approach, development of specially adapted process models could be needed. One result from the surveys is that this integration seems to be used within some of the respondents' companies. Information from the literature survey (**Paper II**), indicates that this type of processes is absent in the academy. In **Paper IV** a generic process model is developed. As this model is of a generic nature, it might need further development to fulfil the purpose of fully integrating TBDA into different development phases as well as be adapted for the use by an engineering designer. For a successful integration of CBDA in general, education and training, in combination with an integrated process model, is important.

5.3.6 Method development for CBDA

Research in the area of method development is not so active in academy, cf, section 3.6 and **Paper II**. The surveys show on the contrary that in method development is widely spread in many companies and used for many different purposes. The use of method development in the development of templates might in the future become as important as its present use in development of analyses procedures for design analysts. Research into method development is thus one area that might require some attention in future research.

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Appended papers

Paper I

Interaction between computer-based design analysis activities and the engineering design process - An industrial survey

Eriksson, M., Petersson, H., Bjärnemo, R. & Motte, D.

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INTERACTION BETWEEN COMPUTER-BASED DESIGN ANALYSIS ACTIVITIES AND THE ENGINEERING DESIGN PROCESS – AN INDUSTRIAL SURVEY

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Keywords: computer-based design analysis, engineering design process, industrial survey

1. Introduction

In the large majority of product development projects, computer-based design analyses of the product-to-be and its components are performed to assess the feasibility of potential solutions. Computer-based design analysis permits an improved understanding of the physical system that is being developed, an increase in confidence in the performed computer-based design analysis activities as well as in the established results from analysis [Eriksson & Burman 2005], an important reduction of physical prototypes, and the possibility to increase the number of design iterations within the same development time [King et al. 2003].

However computer-based design analysis is not present in most of the engineering design methodology literature: in sixteen reviewed textbooks, among others [French 1998; Otto & Wood 2001; Ullman 2010; Haik & Shanin 2010; Ulrich & Eppinger 2012; Dieter & Schmidt 2013], computer-based design analysis is not emphasised in the process models. In the few cases where it is mentioned, e.g. Ehrlenspiel [2003], the German versions of Pahl and Beitz [2005], and the VDI Guideline 2221 [1993], it is only considered as a part of the verification of the product properties and described in a non-operational manner.

Since the overall goal of product development and engineering design methodology is to increase efficiency as well as effectiveness in the development of the product-to-be it is, for obvious reasons, impossible to exclude a likewise efficient and effective integration between the engineering design process and the design analyses activities – here confined to computer-based design analysis. As a first step to bring about a deeper understanding of the actual interaction between the engineering design process and the computer-based design analysis activities, with the overall objective to develop an integrated engineering design and computer-based design analysis process, it was decided to perform an explorative survey in industry. By focusing on how these activities are performed on an operational level in industrial practice, these results are of the utmost importance as a foundation for the establishment of the integrated process model as well as for providing important facts for introducing new analysis concepts in industry. At present, a great deal of interest has been invested in some industrial enterprises in allowing the engineering designer to undertake some of the less complex analyses tasks on his/her own [Petersson et al. 2013].

In order to accommodate the explorative nature of the survey, a semi-structured interview method was utilized; a detailed account of the actual approach is presented below. The structuring of the questions is based on design analysis activities within the engineering design process and thus the interviewees were managers responsible for the computer-based design analysis activities and/or engineering design/product development managers. Furthermore, the survey focuses mainly on the utilization of finite element analysis (FEA) within computational structural mechanics (CSM) simulation. *Note:* Since the survey was carried out between 2007 and 2008 and the analysis of the obtained information from the survey was finalized in 2009, the intention was only to publish the survey results in separate publications. In all, several of the survey results have partly been utilized in three publications [Petersson et al. 2012; Eriksson & Motte 2013a; Eriksson & Motte 2013b]. As the extensive literature survey by Motte et al [2014], covering both the engineering design and the computer-based design analysis literature, indicated that no similar survey was found in the literature and that the survey results were still relevant as of today, it was decided to publish the entire findings from the survey in this paper.

2. Related works

As mentioned above, the engineering design literature focuses mainly on synthesis aspect of the design activity, not on analysis. In the design analysis handbooks, this interaction is on the contrary systematically present, but the interaction with the engineering design process is not elaborated upon. The design to be handled by computer-based design analysis is only present as an input and is then left out of the discussion. The focus is on the analysis task itself, see e.g. [Baguley et al. 1994; Adams 2006], in which the implementation of and managing of the FEA technology in enterprises is discussed with the purpose of providing means for supervising and increasing its effectiveness. A literature review presented elsewhere [Motte et al. 2014] shows that there are several works dealing with the interaction between engineering design and design analysis. However, most of them deal with some specific aspects of this interaction and not for the whole. Moreover, these works are scarce and scattered and do not deal with this interaction on an operational level.

Of these reviewed works, some industrial surveys in that area were found. An early survey by Burman [1992] explored the possibility of extending the use of FEA in the design process, at a time where computer-based design analysis was predominantly used in the later phases of the engineering design and product development process. Burman selected companies developing complete technical systems (TS), e.g. military aircrafts, or complex components (CC), such as heat exchangers and transmissions. Both categories represented companies in which FEA was assumed to be of major interest. A main result is that, already at that time, three out of the ten developing companies reported using design analysis from the conceptual design phase and upwards, experiencing decreased lead-time, decrease resource consumption and better concept selection, pointing out the need for a more extensive use of design analysis in the engineering design process.

A more general survey was carried out in 2001 within the NAFEMS-coordinated FENet project [Knowles & Atkins 2005] with over 1300 replies from more than 40 countries from various industry sectors (although most answers came from experienced users of finite element users from the UK and the US). Although the scale, depth and maturity of FEA in different industry sectors varied widely, the FENet project elicited a number of common issues important for further focus for increased utilization of FEA technology, among others: “Integration of finite element technology and simulation into the wider business enterprise in order to deliver real business benefit,” including product development [Knowles & Atkins 2005, p. 48].

King et al. [2003] have performed a cross-industry study, interviewing five companies varying widely in their use of computer-based design analysis in the product development process (from aerospace company to white-goods manufacturer), and they also pointed out the need for an overall integration of design analysis in engineering design. Their work resulted in a framework considering five aspects for a successful integration of computer-based design analysis and related CAE in the engineering design process: 1) the organization of the product development process (includes planning, management and activities of the development process), 2) software, 3) hardware, 4) support structures for effective use of CAE in the product development process, 5) engineering data management (EDM).

Maier et al. [Maier et al. 2009] have empirically investigated the need for communication between engineering designers and analysts (four engineering designers and four analysts of a German automotive manufacturer), with the aim of improving the effectiveness of collaboration between embodiment design and simulation. It is also not possible to just ‘hand-over’ one’s design to the analyst and consider computer-based design analysis as a black box.

Another survey in Germany has been performed by Kreimeyer and colleagues [Kreimeyer et al. 2005; Kreimeyer et al. 2006; Herfeld 2007, pp. 75-91] in the German automotive industry (both OEMs and subcontractors) to which 33 engineering designers and 16 analysts replied. The goal of the survey was also to get better insight regarding the quality of efficient collaboration between engineering design and simulation departments. Some of their main findings were that engineering designers saw the analysts merely as “service providers” and failed to consider their integrated role in the overall engineering design process; communication and collaboration during analysis planning to set common goals and during analysis result interpretation are seen as key elements.

Finally, a survey by NAFEMS published while this publication was finalized, the NAFEMS Simulation Capability Survey 2013 (1115 respondents), points out that nowadays nearly 30% of the analyses are done during the conceptual design phase [Newton 2013], confirming that design analysis now perspires the entire engineering design process.

The reported surveys have established that there is need in industry for a closer collaboration and integration between engineering design and computer-based design analysis activities. In the presented survey, this need for collaboration and integration is studied at a detailed level: 1) it is investigated for the different types of utilisation of computer-based design analysis in product development; 2) it is also investigated for the different phases of the design analysis activity. Following the framework from King et al [2003], the emphasis is on the process, not on the aspects such as software, hardware and the like.

3. Approach[1]

3.1. General approach

The lack of a commonly accepted terminology creates major problems whenever attempts are made to extract information from the mechanical engineering design process; this is especially valid when design processes in industry are surveyed. To decrease to at least some extent the impact of these problems, a survey technique based on combination of a questionnaire and interview was chosen that already have been proven successful in [Bjärnemo 1991] and [Bramklev et al. 2001]. In this combination, the questionnaire was merely intended to prepare for the interview and was sent to the interviewed people in advance. The following procedure was followed: Potentially interesting/-ed companies were contacted; a letter describing the overall purpose and goals of the survey accompanied the questionnaire; the interviewers then visited the company where the respondents answered the questions sent in advance. All the interviews were recorded.

The selection of the relevant companies is described in the next section. The interviewed persons in each company were generally responsible for performed computer-based design analyses activities at each company and in some of the companies also responsible for the entire product development departments. In some of the companies analysts participated in the interviews.

After each interview, the tapes were listened to and the interviewee’s oral answers to the questionnaire were written down. The document was then sent to the interviewee who had the possibility to complete or adjust it. The corrected document was reviewed against what had been said in the interview to check for any discrepancy. No such discrepancy was found for this survey. Once all the interviews were completed, one person summarized the answers and the points that were deemed relevant to the purpose of the survey were extracted. The other interviewers then shared their view on the summary and synthesis in relation to how they had perceived the interview; following this discussion, an agreement could be reached.

3.2. Selection of companies for the survey

The intent of the survey was both to get an insight into the breadth of use of computer-based design analysis as well as a rough confirmation that the different identified uses were representative (and not exceptions or anomalies). The strategy therefore was to devise a certain number of company catego-

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[1] The organisation of the reporting of the interview process and results have been based as much as possible on the recommendations of [Summers & Eckert 2013] and with reference to [Almefelt et al. 2006].

ries that could give different insights on the use of computer-based design analysis and to have a certain number of companies in each category to see whether there were some replications within or amongst categories. [Bjärnemo 1991] and [Burman 1992]'s categorisation of the companies according to their product types, CC or TS, was deemed relevant for this survey (their products or activities are in, but not limited to, the field of mechanical engineering). However, a third type of company, EC company, was added, as many companies nowadays outsource computer-based design analysis. These three categories of companies are defined as follows:

- The first category consists of those companies developing complete *technical systems (TS)*, as a part of an overall system. An example of a product (system) from this category is a truck, which is a part of a transportation system.
- The second category consists of companies developing *complex components (CC)*, such as turbo machinery and transmissions, for an overall but not explicitly defined technical system.
- The third category consists of *engineering consulting (EC)*, companies that are involved in the development within the companies of the other two categories.

The companies that participated to the survey were all technology-intensive companies in which design analysis were assumed to be of major interest. Their sizes vary from SMEs to large enterprises. The fourteen companies that accepted to respond to the investigation represent five of each of the first two categories and four within the last category. One tentatively contacted EC company turned down its participation to the survey because it did not want to disclose sensitive information about its process. The responses from the EC companies were in general similar regarding their process and therefore it was chosen not to pursue any further interview. Nine of the TS and CC companies have a product development process that is similar to or based on a gate type process, which are available through documents on the intranet. One company is without formalized process but has a number of guiding documents.

Table 1. Company characteristics

Category	Size	Main Industrial Sector	Category	Size	Main Industrial Sector
TS	Medium	Equipment for mining and construction	CC	Medium	Transmission components
TS	Large	Mobile phones	CC	Medium	Brake equipment
TS	Large	Water equipment	CC	Medium	Brake equipment
TS	Medium	Power distribution	EC	Small	Software and consulting
TS	Large	Truck	EC	Large	Development, testing and consulting
CC	Large	Transmission components	EC	Small	Consulting
CC	Large	Turbo machinery in aero application	EC	Medium	Consulting

3.3. Structure of the interview

The structuring of the questions is based on the engineering design process in combination with the authors' experiences within the field of computer-based design analysis activities. The following topics have been brought up. First some questions of general character were asked regarding the company, personnel and its products together with the focus on the *utilisation of design analysis within product development*; the second set of questions were oriented towards the *identification and planning of computer-based design analysis activities*; the third set of questions dealt with *methods and techniques used to carry out the analysis task execution activities*; the fourth set of questions focused on the m*anagement and communication of computer-based design analysis results*; and finally the fifth set of questions was oriented towards the *treatment of uncertainties and errors connected to the design analysis activities.*

The two main reasons for including the treatment of uncertainties and errors in this survey are that on one side the requirements for high level of confidence of the computer-based design analysis results have increased – the companies also want to know more than just the result itself. On the other hand, if the goals of the analyses are not stated clearly, or if the analyses results are not efficiently controlled, the result could be time-consuming activities with an increase in design iteration loops. This could also have implication for the engineering designer who initiates a computer-based design analysis task and integrates its result in his/her work. Such a new area presents also an interest in its own right.

4. Results of the survey

The results of the survey are presented according to the different investigated topics. In general are the results presented for all categories of companies simultaneously, otherwise the particular category is mentioned. A figure at the end of each topic summarizes the findings of the survey.

4.1. Utilisation of design analysis within product development

Use in the different phases of product development: Nine companies are preforming design analysis throughout the complete engineering design process; three are using it only for the later phases of the engineering design process and two of the EC companies mentioned that is primarily driven by customer requests.

Nature of the activity: All companies use design analysis to evaluate product proposals. Three TS and CC companies and all EC companies say that they do product simulation (of the complete system). Five companies out of which three are EC use design analysis methods or tools, such as topology optimization, in the synthesis activities of the concept and product definition. Five of the companies say that the design analysis performed in the later product development phases include a verification step (see definition Section 4.3). Validation is usually carried out with physical prototypes, but four of the TS and CC companies and all EC companies say that they rely on analysis as validation when other means of validation are not possible. Finally, two companies assert that they do phenomenon studies reported from complaints and failure situations.

Occurrence of supplementary analysis: The analyses performed often lead to further supplementary analyses based on advice from analysis department, represented by the analyst, in collaboration with the designers and project members. This is generally very common within the interviewed companies, but the purpose varies greatly. Some of the mentioned purposes are:

- Increase understanding as well as interpret and complement the already performed analysis by third party (externally performed analysis).
- The requirements set out for the analyses are not fulfilled.
- Alternative study due to lack of comprehensive input data.
- When parts and information from customer deviate from given specifications.
- When physical test and analysis results deviates or when a new phenomenon is discovered during testing.

Person or organisation performing the activity: Generally most analyses are performed by the company's internal analysis or simulation department or at least it is their ambition to do so. In certain occasions, however, the companies are outsourcing the analyses due to the following reasons (it should be noted that only the first two listed reasons were mentioned among the EC companies):

- Whenever competence for complex analyses is not available internally.
- When internal resources are not available.
- Simpler and well-defined analyses (because it is possible to get competitive offers on such assignments; these tasks are easily planned and thus uncertainty from planning point of view is reduced; and it avoids repetitive work by own employees).
- When a gain in time and price is expected by external execution.
- In addition, when unaccountable breakdowns and unforeseen phenomena are encountered, an external point of view is interesting.

At two CC companies analysts and designers are considered to be "the same person" (or at least doing the same type of work) and also five companies (three TS and two EC) state that designers have access to analysis software but that it is not used very much or not at all. Five companies say that design analysis is being performed by engineering designers. In those cases, an analyst representing the analysis department is present at least during results review step but often also as support throughout the analysis activities. For two of the five companies where analyses are performed by engineering designers and for one of the companies where analysts and designers were the same person, some guidelines or some form of documents describes the activity.

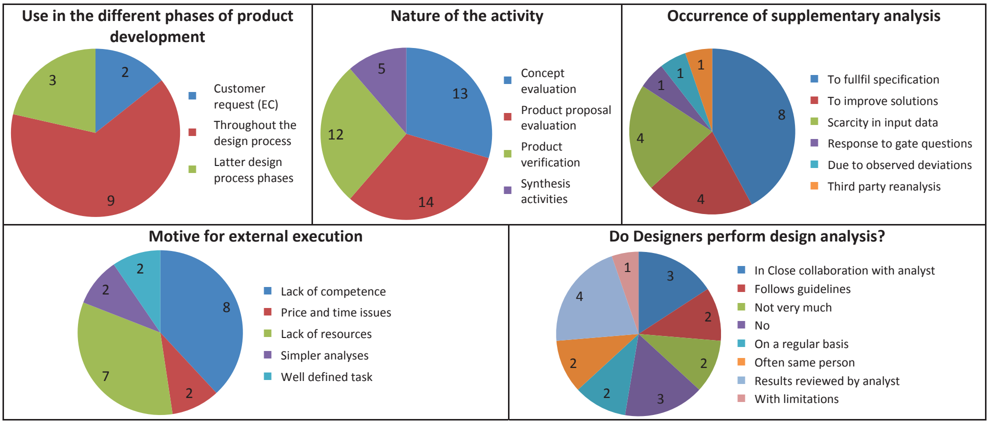

Figure 1. Utilisation of design analysis within product development

4.2. Identification and planning of computer-based design analysis activities

The identification, definition and planning of the design analysis activities are instrumental in a successful execution of the analysis.

Identification and definition of the need for design analysis: Seven TS and CC companies have some form of methodology for identifying and defining the design analysis activity; one of these companies mentions that they has it for critical parts only. The origin of the design analysis need varies and some interviewees mention: customer requirements, product failure mode and effect analysis (FMEA) and test validation. The project leader is often involved in the identification stage together with the responsible person for the design analysis activities in five companies and the responsible person for engineering design activities in four companies. In five of the companies, the engineering designer is also involved and at two companies, the analyst is involved.

Within the three CC and TS companies lacking formal methodology, the knowledge and experience of the analyst or engineering designer performing the analysis activity is instead the basis for the identification and planning stage. The EC companies and one of the TS companies lacking a methodology put forward that generally the customer is often responsible for identifying and defining the design analysis activity. Two of the EC companies mention that they take part in the planning stage while the other two say that it is solely the customer that is performing the identification and definition. One of the EC companies has a dedicated project manager within the organization who is responsible for that activity.

Elaboration of the design analysis specification: Six of the TS and CC companies mention that this is done within the project proposal. EC companies say that it is decided solely by the customer, and only one says that they take part to its elaboration. The most frequent pieces of information mentioned by nine companies (five mention all elements) in the design analysis specification document are: the objective of the analysis followed by loads and boundary conditions, methodology description together with the time frame. Other mentioned elements were background, cost estimate, demarcations, material data, reference to old work and safety factors. Generally, some form of load information pre-exists in terms of load description, load history or load database, for each studied specification.

Planning for execution and follow-up: The adoption of the execution approach and the allocation of resources are primarily based on two approaches:

- Documented best practices are used. Such a document gives guidance, based on gained knowledge from previous design analysis activities, with information on how an analysis is to be performed. Eight companies use this approach.

- The knowledge among the experienced employees and departments involved is utilized as the foundation for establishing the analysis approach. Six companies use this approach.

Also experts within and outside three of the companies are consulted at this stage to gain additional insights to the task ahead.

The follow-up of the design analysis activity are planned to be performed at gate reviews at one of the TS, CC and EC companies respectively.

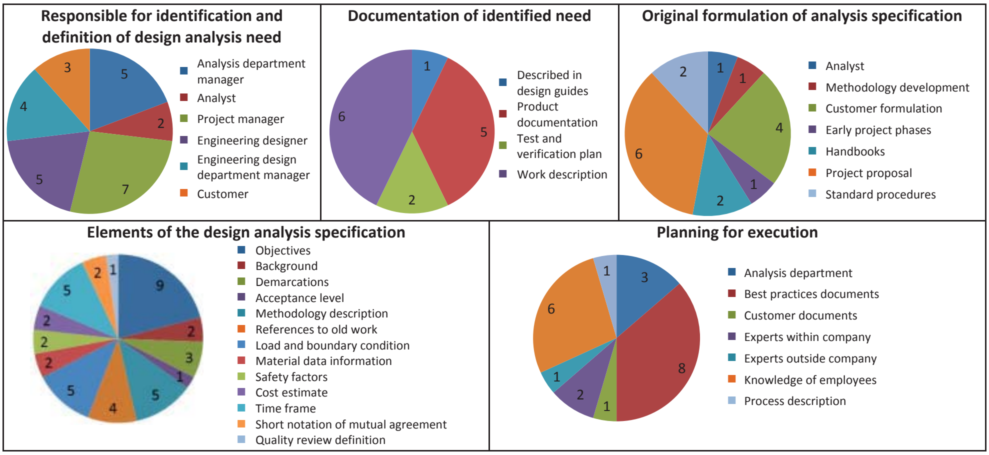

Figure 2. Identification and planning of computer-based design analysis activities

4.3. Methods and techniques used to carry out the analysis task execution activities

Methodological aspects: As mentioned above, execution is based on documented best practices or on the knowledge and experience of the employees. Note that the companies that often have formalised processes for execution are also those companies that have most employees involved in analysis activities within development.

Information support: The discussions within the design analysis department, mentioned by eleven companies, are the most common complementary source of information when assessing a design analysis task and evaluating the results. The documents gathering lessons learned, best practices and methodology description also aid less experienced users and engineering designers to get more acquainted with a design analysis on broad sense, give guidance when performing certain design analyses tasks, and help in the planning of employee education (at six companies). Software support is utilized among eight companies and seven companies have information exchange in corporate networks. Other mentioned channels for information gathering are memberships in organizations such as NAFEMS, involvement in Internet user groups, university contacts and participation to conferences.

Verification and validation (V&V): An approach to establishing a certain *confidence level* both in the future performance of the product-to-be (meeting the product specifications) and in the design analysis procedures utilized, is to use the approach of V&V, which can be defined as follows [ASME 2006]:

- Verification: “The process of determining that a computational model accurately represents the underlying mathematical model and its solution.”
- Validation: “The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.”

More specifically, regarding design analysis, verification is the assessment of the accuracy of the computational model of the design solution, and the validation is the assessment of the accuracy of the simulation results by comparison to data from reality by experiments (by means of prototypes) or physical measurements in working environments. Only two of the companies have really addressed the V&V approach of analysis where validated methods are used for verification. The general approach among the other companies is to have the analyst or collegial review to ensure verification. In addition, three companies mentioned that the analysts perform sanity checks and one company mentioned the use of supporting hand calculations as part of verification. Most companies however address validation the analysis by utilizing physical tests. Some of the companies discuss the physical testing in terms of component testing, system (complete product) testing and three of them also perform field testing, which all have different objectives.

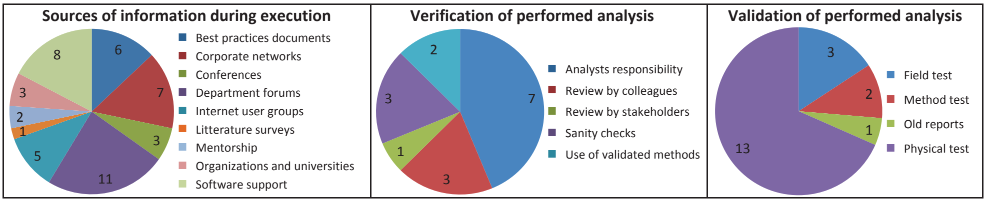

Figure 3. Methods and techniques used to carry out the analysis task execution activities

4.4. Management and communication of computer-based design analysis results

The management and communication of the produced results and information as well as the established analysis files are an important part of the feedback, documentation and future traceability of the performed activities.. EC companies say that both the form of and the content of design analysis outcome feedback generally depends on the customer requirements. The established documentation is presented and discussed at dedicated meetings or gate review meetings within five companies.

At seven companies, effects of design modifications are investigated by some variants of design sensitivity study or other assessment. Furthermore, two companies mention that the documentation should also contain interpretation of the results and engineering suggestions based on the results.

Documentation is stored in data management systems for eight of the TS and CC companies and one of the EC companies. Only one company stores the complete FEA-files in a product data management (PDM) system. One TS company and two EC companies mention that they store intermediate, unpublished, analysis findings such as execution information and results along with gained experience. There exists a model archive at one of the TS companies were each meshed component is saved for reutilization in other analyses. The other companies use a file system also for the reporting.

One company mentioned that it once had a forum in its analysis department where lessons learned should be stored. However, the utilization was very low and the forum was closed after two years. Also one company mentioned that when performing new analyses that is to be based on old data, they experienced that generating the model again is often quicker than try using an old model.

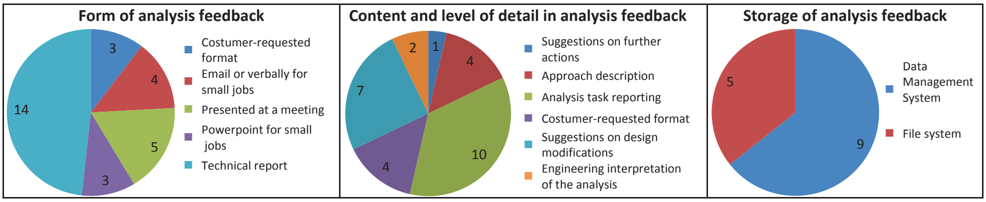

Figure 4. Management and communication of computer-based design analysis results

4.5. Treatment of uncertainties and errors connected to the design analysis activities

From an engineering point of view, uncertainty is present in all areas of design (products, processes, users and organisations). One can distinguish between *aleatory uncertainties* (the inherent variations associated with a physical system or product and also the measuring device utilized to monitor it, also referred to as stochastic uncertainty) and *epistemic uncertainties* (concerned with the possible lack of information or some level of ignorance in any activities and phases involved in performing the planning, modeling and analysis or simulation) [Oberkampf et al. 2002]. The *propagation of uncertainties* throughout the design analysis tasks are often studied though the use of statistical and/or stochastic approaches where a number of analyses are performed to represent the uncertainties of the variables being studied. Another source for shortcomings is the *errors* associated with analysis. The errors are defined as identifiable inaccuracies in any of the activities and phases of the planning, execution and completion of the analysis activity that is not due to lack of knowledge [Oberkampf et al. 2002]. They can be categorized into *intentional errors*, which are inaccuracies identifiable by the analysts and *unintentional incorporated errors*, which are not identifiable by the analysts but are identifiable by others [Oberkampf et al. 2002].

All companies agreed upon that performing analysis would always be affected by uncertainties and errors. However, none of the companies mentioned uncertainties coupled with the validation process or uncertainties from a project or product development perspective.

Aleatory uncertainties: The mentioned aleatory uncertainties are mostly related to variations in the input data to the analysis such as material properties or spread in load data from testing. Two of the companies mention that they address the uncertainty by applying safety factors.

Epistemic uncertainties: The mentioned epistemic uncertainties were often connected to load and boundary conditions, material data regarding damping and fatigue characteristics. One company mentioned uncertainties connected with manufacturing and one mentioned convergence studies to identify and handle epistemic uncertainties. Two of the EC companies and one CC company did not explicitly treat the epistemic uncertainties.

Propagation of uncertainties: Two of the TS company and two of the EC companies mentioned that they regularly use statistical or stochastic approaches to propagate the uncertainties throughout the design analysis activity.

Assessment support: The support when reviewing the uncertainties differs among the companies. Only three of the companies have access to best practices methods when evaluating the response of certain analyses. The common way described is to have a formal or informal discussion with the group or department. One company put forward that sensitivity analyses should always be performed when verifying the established results. EC companies did not mention any specific support system when evaluating the errors and uncertainty with the performed analysis.

Intentional errors: To handle intentional errors three companies rely on a review and check process being performed by a more experienced colleague (in some cases the department manager). Furthermore the resources (time, money and available competence) available for the review of the information available (often just checking the report) are often limited. Also three of the TS and two of the CC companies describes that they rely on sanity checks (in order to rule out any obviously false results) to be performed by the analysts. The interviewed EC companies generally rely on checklists, customer feedback or model regeneration to identify and handle intentional errors.

Unintentional incorporated errors: The presence of unintentional incorporated errors were also acknowledged by seven of the TS and CC and two of the EC companies. This could often be connected to errors in information, data and models provided to the engineer that he/she has no or less control over.

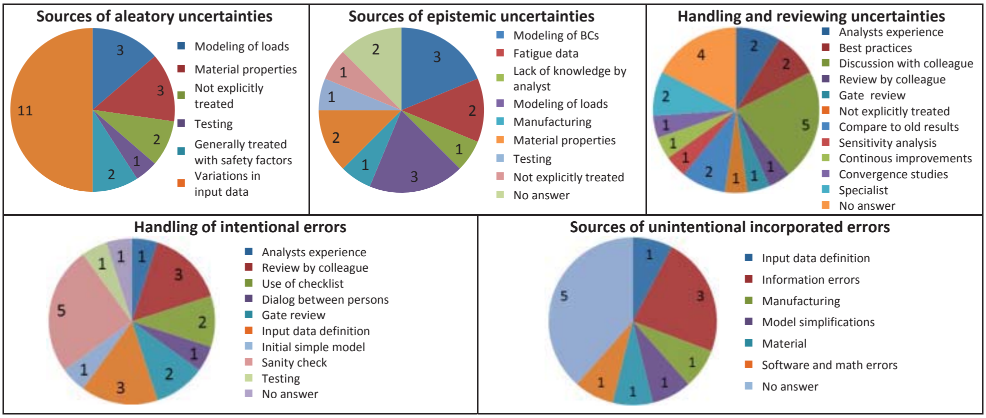

Figure 5. Treatment of uncertainties and errors connected to the design analysis activities

5. Discussion

In this section, the positive and negative aspects of the industrial practices displayed in Section 4 are highlighted. In some cases, recommendations for improvement are provided. Section 5 presents the implications of the results and discussion for future research in that field.

5.1. Utilisation of design analysis within product development

Interaction with product development: Although neglected in engineering design textbooks, design analysis is used often very early during the product development process. New is also the fact that design analysis is not only used for verification but also for synthesis.

In practice however, connection of the design analysis activity to the product development process and available product knowledge at the time of execution is generally lose. The analysis is executed as a somewhat isolated task without proper connection to the parallel activities within the project that initiated the design analysis activity. Also the requirements for and implications of further utilization of the established results and analysis models in forthcoming analyses in later stages of the product development project and the multiphysics integration in a multidisciplinary development scenario were not mentioned by any of the interviewed companies.

Use of design analysis for validation: That several companies also use analysis as a part of validation instead of physical prototypes is also a sign that companies are now very confident in the potential of simulations. On the downside, only two of the above-mentioned companies have really addressed the V&V approach of analysis where validated methods are described in best practices that are used for verification.

Method development: Two among the interviewed companies mention that the need for *method development* connected to design analysis activities is regularly considered. *Technology* or *method development*, in the analysis terminology, is the development and validation of specific guidelines or procedures for the engineering designer or the analyst to follow when performing a design analysis task [Motte et al. 2014]. This can be partially or fully automated. These guidelines define for example which meshing types and approaches are allowed, which load and boundary conditions are to be considered, which results are to be extracted and evaluated, etc. This allows engineering designers to make some specific types of analysis while leaving analyses that are more advanced to the expert. Leaving analysis to the engineering designer has known ups and downs in industries but the use of method development is interesting in that it is a very controlled way of doing design analysis.

5.2. Identification and planning of computer-based design analysis activities

Identification and planning organisation: During the analysis task identification and planning activity, the role of all stakeholders and especially the engineering designer is essential, as he/she is responsible for the assignment of which the analysis results will depend. From the survey it is clear that this should not be done in isolation (with the task specification handed over to the analyst), but in collaboration.

Many times the analysis is planned to be reviewed only after the results is extracted and reported. This is either performed by an experienced colleague and/or by the project steering group at gate reviews. Much resource is thus consumed late in the analysis activities where the possibility to have an impact on the spent resources are limited. Thus, improvement could be gained by early methodology review of the analysis request before analysis is initiated and through continuous collaboration and feedback during the complete design analysis activity.*Elaboration of the design analysis specification:* Many of the companies mention that the translation of product specifications to quantitative analysis specifications is done at the product development project proposal or decision level. Although the majority of the TS and CC companies acknowledged that, the formulation of the design analysis specifications is a high-level activity, one company addresses this only as an early design phase activity with less possibility to act upon and influence the foundation of the activity. Moreover, few if any of the companies discussed the formulations of the analysis specification in terms of other aspects, which have great impact on the information to be expected from the analysis: system level versus component levels, abstract versus detailed descriptions and single physics versus multiphysics properties.

Terminology: The task analysis specification document was denoted differently within the companies such as “start sheet”, “calculation request”, “specification document” and thus a common denomination would be desirable in order to improve communication among companies and individuals for improved understanding. However the content of the design analysis brief itself was usually quite well described, although the following important issues when executing a design analysis task were only mentioned by one or a few companies: Determination of the required level of detail of the results; Elaboration on how the quality assurance of an performed activity should be assessed; Description of monitoring and follow-up actions.

5.3. Methods and techniques used to carry out the analysis task execution activities

The requirements for high level of confidence of the computer-based design analysis results have increased, in other words the companies also want to know more than just the result itself.

None of the companies mentioned connection between the performed V&V activities to assess this confidence and the general quality assurance (QA) program at the company that strives towards establishing a certain confidence level for all activities at the companies. Thus, it seems that this aspect is not as formally described and documented as the best practices for executing the work. Especially the verification activity was given less focus compared to the validation activity. In addition, the distinction and description of the various checks to ensure quality performed by analyst (*self-assessment)* or of *planned checks* performed by an assigned resource (e.g. a senior engineering designer) were scarce. Furthermore, eight of the companies say that they rely on analysis as validation when other means of validation are not possible. This can of course be appropriate in special cases such as for example for one-off products where physical testing is difficult to execute. On the other hand care needs to be taken to ensure that the analysis validation is not only performed as a verification, meaning that only the accuracy of the established model is considered while the requirements from physical test and use situations that the product is intended to satisfy are not taken into account. Furthermore, if the goals of the analyses are not stated clearly, or if the analysis results are not efficiently monitored, the activity could be time-consuming with an increase in design iteration loops

5.4. Management and communication of computer-based design analysis results

Communication of the results: Although all companies state that they present their analysis activities in technical reports, only two of them mention that engineering assessment of the design analysis results are performed. This is somewhat interesting in the light that seven companies mention that suggestion to design modification based on the results are often included in the reporting. Without engineering interpretation of the assumptions and approaches used in order to establish the results at hand, the value of these suggestions might lack adequate foundation.

The documentation should also give information regarding the interpretation of each load on a system level but also broken down to each physical discipline under study and couplings between these in a multiphysics environment. This is an important asset when the design analysis activity is clarified and planned.

Storage and re-use: The companies with most employees involved in analysis have some information exchange in corporate networks between development departments at the different facilities. Interestingly only one CC and one EC company use some form of mentorship to transfer corporate knowledge as well as experience to the newly employed colleagues. Out of the five companies that use Internet user groups as a basis for information search, three of them were EC companies and two were CC companies. Two of the EC companies state that all analyses are saved for the future. At one TS company, the files are stored for ten years; however, the archive is not searchable. Therefore, it is hard for a third party to exploit it. This aspect should be addressed when planning for system to handle the ever-increasing amount of data connected with design analysis activity. Note, however, that on a longer perspective both hardware and software might have evolved so much that opening an old analysis might introduce uncertainties that might be at least as time consuming to assess as establishing a new model. Utilization of already established analysis information when defining and/or performing a feasibility study of a new project is not much discussed within the companies.

5.5. Treatment of uncertainties and errors connected to the design analysis activities

Uncertainties: The lack of control over input data give induces a need for review management of this information. In addition, the uncertainties linked to the product development project have to be addressed, in other words, it is necessary to be ensured that the adequate analysis and evaluations are performed in an appropriate manner. Furthermore, more uncertainties are introduced with parallel evaluation in a multiphysics project and when other disciplines of a product development process (industrial design, manufacturing, marketing sales) are involved. The companies should address this aspect more systematically.

Assessment support: Three of the companies describe that they rely on sanity checks to be performed by the analysts as a part of self-assessment of the results. This is of course a well-founded approach for experienced analysts for justification of their own produced results. However, for a less experienced analyst this can be a problematic task, that in a worst scenario, could lead to incorrect decision. Furthermore, it will most certainly mean that interesting second level information will be lost by the company if lessons learned are not stored within the company.

One company puts forward that sensitivity analyses should always be performed when evaluating the results, however this is not necessarily sufficient: these additional analyses bring understanding to the sensitivity of the utilized model but it is also necessary to have a holistic view on how the model was established in order to ensure a suitable appreciation of the potential uncertainties and errors. It is also concluded that the resources (time and money) available for the review of the analysis results could be increased since this was identified as a bottleneck in many companies. The back-to-back comparison of analysis results is of course a good source of information when performing evaluations of products already known to the company. Nevertheless, it will have less importance when studying new, not previously executed analysis, either by the engineer, department or elsewhere within the company.

6. Conclusion

This survey shows that computer-based design analysis is systematically performed in industry and that it is efficiently done when the identification of the design analysis need, planning for its execution and follow-up is performed in collaboration with relevant stakeholders such as the engineering designer. It is moreover done for different types of problem: analysis of an explorative nature, which is predominantly done in relation with the early synthesis activities, analysis as evaluation and analysis together with physical prototyping. It is also not performed only for evaluation of the design. It should therefore be more present in engineering design process models.

Another aspect that this study has highlighted is method development (Section 5.1). Method development is present in many companies, but has not been emphasized in the literature. Only a few papers in this area have been found, e.g. [Muzzupappa et al. 2010; Stadler & Hirz 2013].

Other areas that from that survey would require further research are:

- Management of the multiphysics analyses: a product is rarely connected with requirements originating from a single physics domain. This has traditionally been handled by execution of independent analysis of each relevant domain. With increased hardware and software capabilities, that area of multidisciplinary and multiphysics analysis have been discussed to get a more complete analysis approach; an example of work in this area is the associative model establishment techniques [Ledermann et al. 2005] for multi-analysis domains. Such aspects should be more systematically considered from the engineering design point of view.
- V&V, uncertainties, sanity checks and the like are all QA instruments for ensuring a better product quality. These are not yet completely integrated in the design analysis process.
- The interviewed companies have a quite clear view of the importance of design analysis for product development, but it is still envisioned as a rather isolated activity. Several aspects such as overall product development project factors are not systematically taken into account, the implication of the engineering designer is often limited to the planning and result steps of the design analysis. An operational process model for a better integration of the design analysis activities in the engineering design process is therefore needed.

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Paper II

Integration of the Computer-Based Design Analysis Activity in the Engineering Design Process – A Literature Survey

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INTEGRATION OF THE COMPUTER-BASED DESIGN ANALYSIS ACTIVITY IN THE ENGINEERING DESIGN PROCESS – A LITERATURE SURVEY

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ABSTRACT

Computer-based design analysis is nowadays a common activity in most development projects. Used for design evaluation, verification, validation, or as a support for design exploration, it fulfils an important support function for the engineering designer, thus making it essential to have an operationally efficient and effective integration between both the engineering design and design analysis activities in the overall development project. In this area, most works are focusing on software (mainly CAD/CAE) integration, but not on the integration between computer-based design analysis and engineering design at the process level or on the collaboration between the engineering designer and the design analyst. This paper presents a review of the literature on that specific topic, namely the integration of the computer-based design analysis activity in the engineering design process. Different research topics are identified and elaborated upon: integration in general process models; recommendations for the different analysis steps; analysis early in the engineering design process; integration of design analysis in the engineering designer's work; alternative usages of design analysis in the engineering design process; and others, such as recommending guidelines instead of process models, quality assurance aspects, education, and implementation issues. Some neglected aspects were also identified. Among others, there is a lack of research into the so-called technology development (development of design analysis procedures and guidelines), and a need for emphasis on uncertainties, both coupled with the design analysis activity.

KEYWORDS

Engineering design process, computer-based design analysis, design and analysis integration, literature survey

1. INTRODUCTION

Computer-based design analysis can today be regarded as a mainstream activity in a development project, more specifically in the engineering design process that is one of the main sub-processes constituting the development process. Traditionally, computer-based design analysis aims at evaluating design proposals and at reducing the need for physical prototyping. Coupled with different exploration techniques (design of experiments, optimization, sensitivity analysis, approximation methods, evolutionary algorithms…) it also permits the investigation of the design space, and it is therefore very useful for the engineering design activity. Computer-based design analysis can take a multitude of forms, from verifying some properties according to a defined standard, utilizing calculators, to very advanced computer-based analyses. In the scope of this paper, the term *computer-based design analysis* only covers quantitative analysis activities requiring the use of advanced computer-aided engineering (CAE) design analysis tools.

The use of computer-based design analysis in the development process involves specific issues. Often, the analysis activity is performed by a specialist, the design analyst (or analyst for short), employed by either the company or an engineering consulting company. Since the analysts and engineering designers work with, and are responsible for, different areas, they do not necessarily have full insight into each other's way of working. They are also utilizing different software, and compatibility problems are frequent. For a successful integration of computer-based design analysis and related CAE in the engineering design process, King et al. [50] propose considering five aspects: 1) the organization of the product development process (includes planning, management and activities of the development process), 2) software, 3) hardware, 4) support structures for effective use of CAE in the product development process, 5) engineering data management (EDM).

Some of these aspects have been the object of extensive research, such as software (CAD/CAE) integration, hardware, and EDM integration, (see e.g. [5;20]), leading towards virtual product development [12;32]. Concerning the first aspect of King et al. [50]'s framework, the organization of the product development process, several works relative to planning and management exist, focusing on collaboration tools [59] between analysts and engineering designers, or other collaboration support [61].

The object of study of the present literature survey is a specific part King et al.'s first aspect, namely the integration of the design analysis and engineering design activities *at the process level*. Different issues are raised at this level, for example, the information needed from each party, the form that the process should take depending on the characteristics of the task (evaluation and verification of design solution proposals, contribution to improvements/modifications of the studied design, supporting the validation of the developed design), or depending on the level of advancement of the project, etc. As computer-based design analysis is present in most industrial development projects, the engineering designers and analysts will need guidance at the operative level. As a first step, it is necessary to know the state-of-the-art in this domain.

The aim of this contribution is therefore to present a systematic review of the works from the literature covering the integration of the computer-based design analysis activity in the engineering design process.

The paper is organized as follows. After having presented the method used for the review, the general research topics identified in this area are described. Then the different research results found for each topic (the bulk of the review itself) are reported. Finally, a synthesis of the main results of the literature review as well as recommendations for further research are presented.

From here on computer-based design analysis will be referred to as *design analysis*.

2. METHOD

Both monographs (handbooks and textbooks) and publications from the engineering design and design analysis literature (papers/articles) have been reviewed, followed by the literature on concurrent engineering. Regarding publications, it was decided to systematically review the contents of the conferences and journals central to both fields.

On the engineering design side the review has been based on most *International Conferences on Engineering Design* (ICED) proceedings (1985-2013), the ASME's proceedings of the *Conferences on Design Theory and Methodology* (DTM), *Design Automation Conferences* (DAC) and *Computers and Information in Engineering Conferences* (CIE) available to the authors (spanning from 1989 to 2013), the *Journal of Engineering Design* (1990-2013), *Research in Engineering Design* (1989-2013), the Journal of Mechanical Design (1990-2013) and the Journal of Computing and Information Science in Engineering (2001-2013). The design analysis review is mainly based on the proceedings of *NAFEMS World Congresses* (1999-2011), *International ANSYS Conferences* (1987-2012), *Simulia Community Conferences* (2007-2013) and *EngineSoft CAE Conferences* (2006-2012), the design analysis journals *Finite Elements in Analysis and Design* (1985-2013) and *International Journal for Numerical Methods in Engineering* (1985-2013) and the related *Computer-Aided Design* (1998-2013) journal.[1] The *ANSYS*, *Simulia*

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[1] Missing years: DAC: 1993-1995; CIE: 1993-1995; ANSYS: 2000.

and *EngineSoft Conferences* are mainly professional conferences dedicated to these specific tools, but Simulia and ANSYS each represent about 30% of the FEA/CAE market and were therefore deemed relevant. The review of works within concurrent engineering has been based on the proceedings of the *Tools and Methods of Competitive Engineering* (TMCE) conference (1996-2010) and on the *Concurrent Engineering: Research and Applications* (CERA) journal (1993-2013).

The review method has been to manually scan the titles of the publications of the proceedings and journals in search of papers describing processes, methods or case studies that could be connected to the process integration theme; and for the relevant identified papers, to utilize their lists of references to find new publications. This procedure is not without flaws: the titles only give information about the main focus of the publication, and works that emphasize, say, software/hardware integration but also discuss the engineering design and design analysis activities may have been missed. However, from the list of references of the identified papers it has usually not been necessary to go back to previously screened contents, which indicates that those works possibly missed might not have been many, or have not been identified in later works.

An alternative method would have been to perform a database search, but because of the high frequency of the searched keywords (“integration”, “design analysis”, “simulation”…) in different scientific fields, this strategy was not adopted.

For older publications, the results from an earlier literature survey by Burman [19] were used and incorporated in this review. In his comprehensive literature review (306 monographs and 225 articles), Burman [19] revealed that although many authors called for a better integration of design analysis in engineering design, works in that direction were in effect very limited. Only 18 publications and 2 monographs were found to couple design analysis and the engineering design process.

The concurrent engineering literature was screened after the engineering design and design analysis literature, preliminary with CERA and TMCE. Apart from a few exceptions, the reviewed works dealt with the same general topics as the two other disciplines, with several authors publishing in both concurrent engineering and engineering design or concurrent engineering and design analysis. It was therefore decided not to extend the review further.

During this search it became apparent that many works have emerged within the German-speaking research community. The review of the German publications could not be as thorough as for the English-speaking ones, for pragmatic and theoretical reasons. First, the German engineering design and design analysis literature is almost as large as the English, and it would have required a much larger total effort. The earlier paper-based publications were also more difficult to obtain. Second, many of the elements found in the German literature were also present in English. The important German works are nevertheless reviewed in this study. A literature review of the German literature has been found in the dissertation by Herfeld [46]. His review focused on the first of the identified topics presented next (“General process models”) and has helped identify subsequent works.

The literature search within concurrent engineering also revealed that the Japanese industrial research community is quite active in the area under scrutiny, but the language barrier prevented investigating this further.

The review has been restricted to FEA-based computational structural mechanics (CSM) simulation publications. Journals and proceedings from other design analysis areas such as computational fluid dynamics (CFD) and multibody simulation (MBS) have not been systematically reviewed, although some works from those areas are reported in the present publication. The main reasons are that CSM simulation is the most widespread type of design analysis, and the few works from the CFD and MBS areas were of the same nature as those found in the CSM field.

The reviewed publications are not all presented in this work. The complete list of publications can be made available on request.

Once the relevant publications had been identified, they were categorized according to the topics the papers dealt with. These main topics and the results from these works have then been summarized in the following section.

3. GENERAL TOPICS OF THE REVIEWED PUBLICATIONS

The integration of design analysis in the engineering design process is virtually unmentioned in the engineering design textbooks reviewed, apart from a few German books, but it is more frequently present in the design analysis textbooks. This is in fact necessary for the latter, as design analysis almost always depends on the existence of a design proposal, while engineering designers in many design projects may exclude the use of design analysis. However, many works simply consider design as a “black box”, irrelevant to the design analysis process.

213 papers have been found, 124 from the engineering design literature, 55 from the design analysis literature, 22 from concurrent engineering and 12 that could not be classified. Of those, 176 are publications in English. It can also be incidentally noticed that the number of publications in German reviewed, 33, is found mostly in the engineering design literature (31), representing around 25% of all the publications in this domain. If one adds the English publications published by German institutions, this amounts to more than 40%.

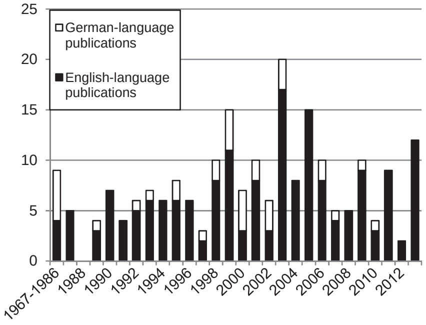

Figure 1 Number of publications per year

The total number of publications can be considered as quite low in comparison to the thousands of publications that have been screened. Moreover, the scope of the papers regarding the integration of design analysis in the engineering design process varies widely: some publications are dedicated to the subject while others only treat it anecdotally. Figure 1 shows the number of publications on this theme over the years. In fact, several papers are heavily clustered around a few specific founded research projects and programmes, which is reflected in the histogram: projects on implementation of finite element analysis and evaluation procedures in the engineering design process in Sweden in the early 90s [15], “Innovative, computer-based engineering design processes” programme of the German Research Foundation [66] in the mid-late 90s, the Integrated Virtual Product Development (iViP) key project [54] in the early 00s and the ongoing FORFLOW research alliance [55;72] in Germany, and active research mainly at Toshiba and Kyoto University in the early-mid 00s in Japan [52;53]. Some institutions have also been recurrently publishing on the subject (Technical Universities of Munich, Berlin, Erlangen, University of Bath…). There seems also to have been a specific interest in integration in the late 90s and early 00s in the design analysis community (special sessions at the *NAFEMS World Congresses* in 1999, 2001 and 2003, the FENet project founded by the European Commission between 2001 and 2005). The remaining papers are mostly isolated works. The heights of the odd-year columns from 1999 are explained by the ICED and NAFEMS conferences.

The *main research topics identified* are: 1) Integration in general process models, 2) Recommendations for the different analysis steps, 3) Analysis early in the engineering design process, 4) Integration of design analysis in the engineering designer’s work, 5) Alternative usages of design analysis in the engineering design process (other than design evaluation), 6) Others, such as 6a) recommending guidelines instead of process models, 6b) quality assurance aspects, 6c) engineering education, 6d) implementation issues, and 6e) miscellaneous themes. A number of accounts and reports from industry (survey or case studies) have also been found. The number of publications for each category is represented in Figure 2 (the industrial accounts and reports category is numbered as 7).

Some publications take up several topics, which is why the total number of 321 publications presented in Figure 2 is larger than the total number of reviewed publications (213). From Figure 2 it can be seen that most works deal with the integration issue in the form of general design or analysis process models. Many publications also give accounts from industry. A large number of publications have been classified as “Others”, representing topics that have been the object of fewer research works. Keeping in mind that engineering design literature is represented twice as much as design analysis literature, it can be seen that recommendations to the analyst (category 2) and educating the engineering designer (category 6d) are important in design analysis research while work on alternative usages of design analysis in the engineering design process (category 5) is mostly present in engineering design research. 19 publications from concurrent engineering have been found. As this literature has been reviewed less systematically, there is little point in comparing it with the other two domains. Figure 2 shows that most categories are also represented (except 6d and 6e) with a majority regarding applications (category 7).

Other categorization systems than the one introduced above might have been possible; this one has the advantage of being near the recurring themes heard of from various experiences in industry (especially categories 2-5, 6b, 6d) or that can be a useful basis for further research (e.g. category 1).

4. CURRENT RESEARCH ON INTEGRATION OF THE DESIGN ANALYSIS ACTIVITY IN THE ENGINEERING DESIGN PROCESS

4.1. Integration in general process models

As mentioned above, engineering design textbooks and handbooks (16 were reviewed) do not emphasize design analysis activity in their process models. The exceptions from the German literature are Ehrlenspiel [36], the German versions of Pahl and Beitz starting from the very first edition of 1977 [73], and the VDI Guidelines 2221 of 1993 [88] and 2211-2 of 2003 [89]. Ehrlenspiel [36] mentions that design analysis and simulation are basic design activities for design proposal evaluation. Design analysis is mentioned in Pahl and Beitz [73;75] in a specific chapter on computer-supported engineering design where computer-based tools are introduced in the general engineering design process model. The part concerning analysis is not detailed, and is mostly descriptive. This chapter has been re-written in all subsequent versions but has never been integrated in the main chapters dealing with the synthesis activities of engineering design. This chapter was not included in the English versions (except in the first one of 1984 [74]). The VDI Guideline 2221 of 1993 [88] presents the same model as Pahl and Beitz', who were among the main writers of the guideline. The VDI Guideline 2211-2 of 2003 [89] gives recommendations on the use of design analysis within the engineering design process of VDI 2221 (see Sections 4.3 and 4.5).

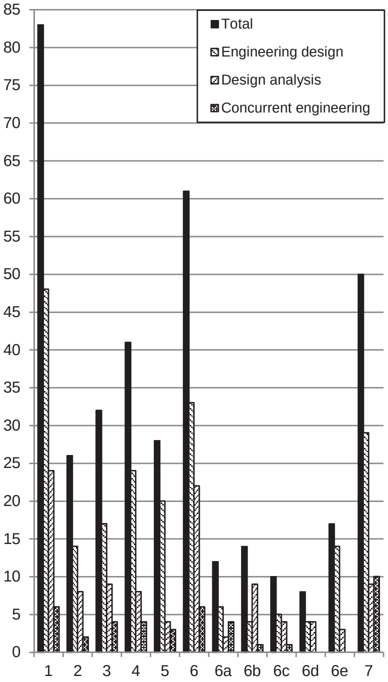

Figure 2 Number of publications per identified topic. The 12 non-classified publications are included in the Total column

In the design analysis literature, this interaction is on the contrary systematically present. In the early design analysis literature, the procedures describing the use of design analysis in the context of design analysis focused on solving analysis problems accurately and efficiently with a set of developed and outlined techniques and methods [13;26]. The design to handle is present as an input, but the interaction with the engineering design process is not elaborated upon. With the further development of software and generalization of the use of such numerical methods, process models have eventually been developed and encompass different industrial aspects in order to support the practitioner's work. NAFEMS (originally the National Agency for Finite Element Methods and Standards) has proposed several models during recent decades that have been influential in industry. For example, in Baguley and Hose's *How to plan a FEA* [11], the workflow of design analysis tasks is extended to include steps that couple analysis to the design or development project: it encompasses for example tasks that are project- and enterprise-related: preparation and agreement of specifications, preliminary calculations in order to allow resource estimations, etc. Other subsequent works are [4;5;60].

Regarding papers and articles, some publications, especially early ones, discuss this integration, such as [23] and [17], where a thorough study of how to use FEM in all phases of Pahl and Beitz [74]'s systematic engineering design process (including task clarification) was undertaken and its benefits emphasized. Different tools and methods in the different phases of the engineering design process are discussed in [7;62;64] where among other things MBS and FEM analyses as well as topology optimization are already recommended at the conceptual design level, and shape optimization at the detail design level [7].

Design analysis is more systematically mentioned in specific engineering design process models, notably in re-design processes [71] but not dealt with specifically. Some engineering design process models have been proposed that integrate analysis for dealing with specific engineering design activities — integration of CAE in design for mechanical reliability and maintainability [45], integration of durability (fatigue)-related design analysis tools early in the design process [58, p. 114], geometric deviations and deformations [48].

4.2. Accounts and reports from industry

Accounts and reports from industry have been found in the form of surveys and case studies.

There have been regular industrial surveys reporting that companies are striving for a better integration of both processes. In a survey by Burman [18], 3 out of the 10 developing companies reported using design analysis from the conceptual design phase and upwards, and he points out the need for a more extensive use of design analysis in the engineering design process. A more general survey was carried out in 2001 within the NAFEMS-coordinated FENET project [51] with over 1300 replies from more than 40 countries from various industry sectors (although most answers came from experienced users of Finite-Element users from the UK and the US). Although the scale, depth and maturity of FEA in different industry sectors varied widely, the FENET project elicited a number of common issues important for further focus for increased utilization of FEA technology, among others: “Integration of finite element technology and simulation into the wider business enterprise in order to deliver real business benefit.” [51, p. 48], including product development. A subsequent survey by NAFEMS, the NAFEMS Simulation Capability Survey 2013 (1115 respondents) points out that nowadays nearly 30% of the analyses are done during the conceptual design phase [68]. King et al. [50] have interviewed five companies, and they also pointed out the need for an overall integration of design analysis in engineering design. Maier et al. [61] have empirically investigated the need for communication between engineering designers and analysts (4 engineering designers and 4 analysts of a German car manufacturer). Finally, a survey has been performed by Kreimeyer and colleagues [46, pp. 75-91;56;57] in the German automotive industry (both OEMs and subcontractors) to which 33 engineering designers and 16 analysts replied. The goal of the survey was to get better insight regarding the quality of efficient collaboration between engineering design and simulation departments. Some of their main findings were that engineering designers saw the analysts merely as “service providers” and failed to consider their integrated role in the overall engineering design process; communication and collaboration during analysis planning to set common goals and during analysis result interpretation are seen as key elements.

The case studies were generally found in the heavy and high tech industries: FEA in a military application [22], examples drawn in electronics, electrical engineering, and mechanical engineering domains in [91], aerospace industry [70], railway transport [3], automotive industry [29;48], capital equipment [47],except for a few exceptions such as [41] — use of CFD in the traditional home appliance sector — or [82] — analysis of a child carrying board. These case studies generally show the advantages of incorporating design analysis in the engineering design process for specific industrial branches, while warning about the practical difficulties of implementing it. In line with the survey above, they generally criticize the lack of integration between engineering design and design analysis activities. As noted in [41], general discussions about such integration must be completed with practical guidelines. Adams [3]’s case study also shows that companies focus too much on the software integration and less on process integration or on proper education.

4.3. Recommendations for the different analysis activities

The different analysis activities can be divided into analysis planning, analysis execution (pre-processing, solution processing, post-processing), and analysis results interpretation and communication. Ciarelli [22] illustrates concisely the shortcomings of the traditional interactions between the simulation and design activities for the different analysis activities. Concerning analysis planning: “Starting with only limited design information, the specialist must then formulate a detailed design problem which simulation can address and determine the design data and simulation tests required to render a solution. Even when further inquiries are made to the design engineer regarding the accuracy of the formulated problem, communication problems stemming from limited understanding of the respective fields greatly limit the exchange of significant observations." (p. 16) During execution, engineering designers are often not in control either because of their limited knowledge of the simulation tools, their possibilities and limitations, or because of lack of feedback information on the execution progress, while on the contrary "simulation specialists are restricted to focus on applications, which limits their understanding of the product design requirements and leads to less appropriate analyses" (p. 16). Finally, result and communication shortcomings are exposed: "the specialist assembles the results in a report which is meaningful to him/her and which adequately represents the effort which was extended to complete the simulation. Too often absent from the motivation for the report are concern for how the design engineer will use the results and the future reuse of the simulation model" (p. 16). Adams [2, p. 63] also exposes the necessity of having good communication between the designer and the analyst.

Most of the recommendations concern planning. Operational procedures can be found in [8;8;76;87]and a set of factors, exogenous to the design analysis activity but affecting it, important for planning, are discussed in [40].

For the execution activity (pre-processing, solution evaluation, post-processing) a few support guidelines and tools have been found. Adams discusses the importance of having a CAD file as input that allows for proper idealization (representation "of the true geometry with more complex element definitions or a simplified representation" [2, p. 63]), and of having defined boundaries of the analyzed part with the interfacing parts of the whole technical system. He also recommends that three persons be involved in the process: the engineering designer, the analyst and a supervisor to control for quality. In Mertens [65] and the VDI 2211-2 [89], the "ABC concept" is proposed: choosing design analysis methods according to two criteria: the time required for analysis execution and the accuracy of prediction (informativeness) required by the engineering designer. Examples of recommendations are given according to three levels of time and accuracy (A, B, C), level A being the most demanding in terms of time but having greatest accuracy. Examples of recommendations are the use of "rules of thumbs" and analytical calculations in level C, the use of linear FEM in level B, the use of non-linear FEM and the hiring of a professional analyst in level A. Deubzer, Herfeld and others [31;46] proposed a matrix-based tool coupling components and functions intended to enhance communication — this allows the analyst to have better support for deciding which product element to include or not in the analysis.

4.4. Analysis early in the engineering design process

There has long been an interest in using the capabilities of design analysis earlier in the design process, because many decisions that have a large impact on the whole product development are taken early, and also to "save time and money by avoiding expensive and time-consuming prototyping" [91, p. 7]. This implies, among others that: Simplified, dedicated design analysis tools are available for conceptual design, e.g. [33;86], which can be used during the search for and combining of solution principles and to firm them up into concept variants [17]; The engineering designer must do part of the analysis activity and have skills in both modeling and result interpretation; It is necessary to write the design requirements using an "FEA-oriented formulation" [17]. The NAFEMS Simulation Capability Survey 2013 mentioned above [68] shows that design analysis in the conceptual design phase is now common practice.

4.5. Integration of design analysis in the engineering designer's work

Because of advances in software development (not only the obvious time- and cost-saving effects, but also the benefits for the design (synthesis) activity), there has been a recurring promotion for letting the engineering designer perform design analysis activities. Hence, it has been repeatedly recommended to train engineering designers in computer-based design analysis, and for the software companies to adapt software to these specific needs [79;92]. However, all authors state clearly that the analyses performed by engineering designers should be limited to well-formulated, delimited, small, routine or basic design analysis tasks [41;84]. The engineering designers can get help from the so-called "first-pass" tools for exploring some ideas and quickly eliminate non-viable proposals [80;85], but thorough verification should be left to the analyst [41;78].

The guideline VDI 2211-2 [89] is to that end instrumental by presenting recommendations for an efficient and moderate use and integration of design analysis in the engineering designer's work (see also Section 4.3).

Research about, or reports on, general technology development or method development was also investigated. Technology or method development, in the analysis terminology, is the development and validation of specific guidelines or procedures for the engineering designer or the analyst to follow when performing a design analysis task. This can be partially or fully automated. These guidelines define for example which types of meshing are allowed, which loads and boundary conditions are to be considered, which results are to be extracted and evaluated, etc. This allows engineering designers to make some specific types of analysis while leaving more advanced analyses to the expert. Technology development or method development is present in several companies and is mentioned in the NAFEMS Simulation Capability Survey 2013 [68], but only a few papers in this area were found, e.g. [67;83].

4.6. Alternative usages of design analysis in the engineering design process

The main implicit usage of design analysis in most publications is evaluation of design proposals. Some other usages are nevertheless possible. One extension of design analysis is to couple it with an optimization system [21]. Importantly, this is in the direction of using design analysis *in* synthesis. Optimization is generally considered to be adjustments of well-defined parameters in the detail design phase of the engineering design process, but it can be used much earlier, see e.g. [38].Another case in point is the use of topology optimization for the design analysis part.

Beyond optimization, design analysis tasks can be used to orient the engineering designer in his/her search for solutions, to make analysis of “exotic” ideas [28], to make early quick analyses of design proposal and get valuable information [28], or to explore “what-if” scenarios [6]. The concept of predictive design analysis or predictive engineering [16;37;63] has also emerged, which extends the use of analysis in engineering design from a function of verification of potential solutions to that of predictions and guidance for further development of these solutions. An illustration of its use throughout a whole development project can be found in [38].

Design analysis is often discussed in relation to the product-to-be, but this is limiting. Design analysis can be used for material investigation [42;90] or other product-related element such as packaging or packaging machinery [47].

In recent years researchers have begun to extend the interpretation of design analysis into a different direction that is frequently referred to as simulation-enabled, simulation-based or simulation-driven product design, meaning that an extensive utilization of design analysis activities to address the evaluation of the properties of the product-to-be will increase the efficiency of engineering design [27;43]. Other approaches also presented under the same denomination imply that the decisions within the engineering design process should be based primarily (or even exclusively in some cases) on the analysis outcome; see [4;81]. The fundamental idea is that a representation of the product-to-be is established on which the analyses, evaluations and decisions should be based. The accuracy and applicability of the design analysis model is ultimately validated on the virtual product, through virtual testing, not on a physical validation object. This approach introduced an interesting perspective. However, as stated in [44], when considering that all design analysis models are based on the fundamental assumptions and limitations accompanying design analysis, this approach tends to overestimate the current possibilities of design analysis. Also bearing in mind that design analysis is generally only capable of addressing a subset of all aspects connected to an engineering design project, the simulation-driven design approach seems to promise more than it currently can deliver.

4.7. Others

Some publications dealing with the integration of design analysis in the engineering design process address themes that only partially fit the categories above and have been regrouped here.

Some works, rather than discussing the design analysis integration as a process, have proposed developing guidelines to match engineering design problems with relevant design analysis techniques [2;33;77].

Importantly – and quite naturally — some works from concurrent engineering insist on a parallel activity of engineering design and design analysis and its positive implications for an effective product development [24;25;35].

It is also necessary to take into account the enterprise configuration in which the design analysis takes place. The most common configuration is the use of in-house design analysis competence, but in many cases the design analysis is delegated to an engineering consulting company. In that case, the necessary knowledge and competences are split among companies, the analysis standards and procedures must be agreed upon, etc. This aspect has been neglected in the literature, although it significantly impacts the effectiveness of a design analysis task. A broader discussion can be found in [40].

The role of quality assurance in design analysis for its integration in the engineering design process is also brought up [4;39]. It emphasizes feedback to the engineering designer, since any relevant and required additions and modifications to the task are captured, updated and communicated through quality management before the solution-finding activities and results are delivered. This reduces the risk of utilizing unnecessary time and resources as well as providing irrelevant results.

Several authors discuss the importance of properly educating engineering designers in design analysis in order to be able to make their own preliminary analyses with an awareness of recurrent pitfalls in that area and to be able to communicate with specialists [3;62].

Finally, some works discuss the implementation of design analysis in the engineering design activity so that the whole process is more efficient and proceeds without friction. King et al. [50] present a "good practice model" for implementation of computer-aided engineering analysis in product development (already mentioned in the introduction). Fahey and Wakes [41] discuss the implementation of CFD analyses in a company, and their guideline recommends to have realistic expectations, to have good knowledge of the underlying theory, to have a model fidelity that corresponds to the state of progress of the design, to be aware of the level of confidence of the results, and to have flexible models for re-use. Curry [28] recommends not introducing completely new methods at once, but combining old and new ones so that the transitional phase is achieved more smoothly. Adams [4] indicates that management support is essential for a successful implementation. In another publication, Adams [1] warns that analysis "will be a bottleneck" (p. 727, emphasis in original) in the design process. It is therefore necessary to be ready for it. Often, too, the company's strategy for implementing design analysis is to adapt it to existing methods and tools; according to Adams [1], however, this would greatly limit its use, notably during early design. Lastly, *both* the engineering designers *and* the analysts should have enhanced knowledge about their respective activities and role in the design process [4].

5. DISCUSSION AND CONCLUSION

5.1. State of the literature

Based on this systematic investigation, it can be stated that research on the integration of engineering design and design analysis at the process level is scarce and scattered (see Figure 1). There are very few cross-references between research groups, and many stand-alone works. Only the German literature presents a greater continuity. The intention has been to make this review as comprehensive as possible, and it is hoped that it can be used as a basis for further research.

This integration aspect is also by and large ignored in the mainstream literature (engineering design textbooks and handbooks), although the many case studies reported show that this aspect is important in many industries where products are systematically developed with the help of design analysis, and that compelling cases for better integration can be found [1;22].

One reason may be that research in engineering design has shifted more and more towards synthesis (creative methods, cognitive studies of the engineering designer) and the contextual aspect of engineering design (activities linked to need finding, collaboration, and the like). According to Birkhofer [14], because of the increasing specialization in these areas this trend is going to continue: "the worlds of Design Methodology and CAX technologies, with their models and procedures, increasingly draw apart." [14, p. 9]

Another reason is the general appraisal that this integration issue is best tackled through software (CAD/CAE) integration, data integration (EDM, PLM) and automation (e.g. KBE systems) [34]. Such an approach has undoubtedly been successful but it is not a panacea and does not solve all activity-related integration issues.

It is finally important to note that the literature review has focused on works of a general nature. There are, however, publications dedicated to specific branches, such as the military or oil and gas industries, where recommendations for both the design and analysis of specific equipment are proposed. Such works are presented for example in the form of standards (e.g. [49] for offshore structures), best practices (e.g. [30]) or guidelines (e.g. [10]). These are not reviewed here but might have some aspects that could be taken up in more general works on the integration of design analysis in the engineering design process.

5.2. Key recommendations from the literature

From the literature review, the following key recommendations for better integration have been extracted. They concern both academia and industry. Especially, recommendations for integration of design analysis in the engineering designer's work should be valuable for industry, as many companies are regularly trying to cut delays and costs by assigning the design analysis activity to the engineering designer with many potential shortcomings:

- Make design analysis activity an integral part of the engineering design process (Section 4.1), not necessarily in the form of a design process (cf. Section 4.7).
- Educate the engineering designer in design analysis (Sections 4.5 and 4.7).
- Limit design analysis performed by engineering designers to well-formulated and delimited routine and basic design analysis tasks (Section 4.5).
- Do not reduce design analysis to an evaluation technique (Section 4.6). Design analysis can be used for guidance, exploration and optimization, and not only for the product-to-be (e.g. material research).
- Increase communication between the engineering designer and the analyst, especially during planning, so that the "right" design analysis problem is solved.
- Enhance coupling between design analysis, engineering design and quality assurance (Section 4.7).
- Implementation of such integration is not straightforward and must be carefully managed (Section 4.7).
- Earlier design analysis allows for quicker verification (Section 4.4).
- Take into account the enterprise configuration in which the design analysis activity takes place (Section 4.7)
- At the task level, emphasize the design analysis planning, which impacts the whole analysis task and results. Planning for design analysis early is also more efficient (Section 4.3).

5.3. Further domains of enquiry

Although the topics developed in the reviewed papers are quite broad, some important themes have not been given the attention they deserve.

The verification and validation (V&V) methodology (see definitions in [9]), is one such theme. V&V focuses on the verification of the analysis model (accuracy of the computer model in comparison with the established design problem) and on the validation of the accuracy of the simulation results by comparison with data from reality by experiments (by means of prototypes) or physical measurements in working environments. Because these two activities are time-consuming they should be planned together with those responsible for engineering design. Moreover, as prototypes are made, synergies could be found between both analysts and engineering designers.

There is also a need to complement general discussions about such integration with operational, practical, guidelines [41]. It is in other words not enough to only have a general process model. More hands-on recommendations are needed.

Finally, from an engineering point of view, uncertainty is present in all areas of design (products, processes, users and organisations). Taking into account uncertainties, with dedicated techniques throughout the design analysis activities, is important in order to provide other stakeholders with a certain confidence in the decisions based on the design analysis task outcome. The approaches discussed do not explicitly handle the dilemma concerned with variability and uncertainty that is associated with design analysis; see e.g. [69].

5.4. Perspectives

In neglecting the integration of the design analysis activity into the engineering design process, two risks arise. From the educational point of view, there is a risk, in minimizing the place of verification and validation aspects in the engineering design activity, that the engineering design student will not get an overall picture of the whole engineering design process. But there is also the risk that further developments in design methodologies will fail to evolve in alternative directions, such as focusing on risk-elimination and uncertainty-assessment design strategies.

Similarly, there is also a risk in promising too much from design analysis without acknowledging its current limitations and specific characteristics, which can potentially lead to design analyses in certain situations being considered a bottleneck or, even worse, that trust in the methods is lost. Therefore, work towards holistic integration of design analysis activities into the product development process, together with actions receiving endorsement from management and other stakeholders, are central future research areas.

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Paper III

The Engineering Designer in the Role of a Design Analyst – An Industrial Survey

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THE ENGINEERING DESIGNER IN THE ROLE OF A DESIGN ANALYST – AN INDUSTRIAL SURVEY

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Abstract

Traditionally, design analysts are solely responsible for all computer-based design analysis (CBDA). CBDA refers to quantitative design analyses utilising computational tools in the engineering design and development of technical solutions. There are currently limited insights into and knowledge of tools and methods needed to facilitate the use of CBDA by engineering designers. In order to gather information on this aspect of CBDA, an industry survey has been performed.

77 persons completed the survey (16% affiliated to NAFEMS) open for twelve weeks during October-December, 2014. Around 35% answered that within their companies CBDA is used by engineering designers, and 28% of those who are not currently doing so expect to do so in the future. Linear static analysis is the most frequent type of analysis performed by engineering designers. The benefits put forward by the respondents in favour of involving engineering designers in CBDA are: it allows early evaluation of concept candidates, shortens lead time, frees resources for the analysis department, and reduces costs. 26% of the respondents answered that there is resistance from the analysis department against allowing engineering designers to perform CBDA, 19% within the engineering design department are also against this involvement and 26% answered that there has been no problem associated with this involvement.

Even though the engineering designer performs CBDA on his/her own, supervision (56%) and quality assurance of the analysis results (59%) is the responsibility of the design analysts. This is also the case regarding the development of tools and methods to be used by the engineering designers as well as instruction and training of the engineering designers.

1. Introduction

During an engineering design project, the traditional process is that when the engineering designer has developed a concept, product architecture or detailed design solution, these are sent to the design analysis department, which performs the actual computer-based design analysis (CBDA). CBDA refers to quantitative design analyses utilising computational tools in engineering design and development of technical solutions. CBDA is here confined to structural analyses using the finite element method (FEM), computational fluid dynamics (CFD), and multi-body system (MBS), also including supportive tools such as knowledge ware and optimisation tools (shape optimisation, topology optimisation and others)—all within mechanical engineering. A CBDA project might have a number of different objectives, such as evaluation of technical solutions or exploring design parameters in order to validate the working principle for a specific solution or optimise the performance of an actual design.

The influence of the lead time of a CBDA task is substantially dependent on the engineering design project from which it originates. One reason for this is that the design analysis department analyses many different products and designs, most often involving a huge variety of analysis problems, and thus makes it necessary to prioritise the CBDA projects with reference to the priority of the engineering design project from which it originates. Low priority indicates that the lead time will be longer than for a product of higher priority. One example is the evaluation of new concepts, in some companies it has a low priority, the lead time for this type of analysis can sometimes be as long as 6 - 12 months [1]. This may well give rise to situations where engineering designers will focus on more urgent problems than designing new concepts, thus increasing the risk that the company will produce less innovative design solutions.

One solution to this problem is to involve the engineering designers to perform CBDA in a controlled form. The considerable development of CAD-CAE systems, their usability and improved integration, makes that feasible. However, engineering designers will never have the same level of knowledge and experience as design analysts, which increases the risk that the design solutions analysed will still be flawed when they arrive on the design analyst’s desk for verification, thereby neutralising all positive effects. The question of cost is also important. If engineering designers are allowed to perform CBDA, instructions and training will be required as well as support, supervision, and possible software adaptation, not to mention the larger number of expensive licenses.

The main objective set out for this paper is to give an overview of the current situation in industry regarding CBDA tasks being performed by engineering designers, what positive effects it might present to the industry and how it should be implemented for best result. This has been done by means of a survey addressed to members of engineering associations such as NAFEMS and ASME, as well as targeted companies. The main subjects touched upon by the survey are the proportion of companies applying this approach, the type of support used by the engineering designers, the degree of freedom they have, and the challenges associated with this approach.

The paper is outlined as follows. The next section presents related works and background information on the topic. The general approach chosen for this investigation, the selection of respondents and the structure of the questionnaire are then reported. This is followed by the presentation of the results from the answers of the respondents to the questionnaire. The paper ends with a discussion of the results and a conclusion on how the results can be used in the future development of CBDA methods and tools for use by an engineering designer.

2. Related work

This survey focuses on what positive effects the industry might gain from letting engineering designers perform CBDA and how it should be implemented for best outcome. Works that touch on this topic are reviewed below.

In the literature, it has been repeatedly recommended that engineering designers should be trained in CBDA and that software companies should adapt software to their specific needs [2; 3]. However, all authors state clearly that the analyses performed by engineering designers should be limited to well formulated, small, routine or basic design analysis tasks [4; 5]. The engineering designers can get help from the so-called “first-pass” tools for exploring some ideas and quickly eliminate non-viable proposals [6; 7], but thorough verification should be left to the analysts [4; 8].

In order to ascertain how widely the approach of letting the engineering designers perform CBDA is used in the industry, surveys were also reviewed. The EASIT[2] survey from 2011 [9]—1094 respondents from 50 different countries—gave a broad perspective on the use of CBDA in industry; the NAFEMS Simulation Capability Survey 2013 [10]—1115 respondents—shows that CBDA is now used in all phases of a development project, with 30% of all analyses done during the conceptual design phase. However, in these surveys, the proportion of design analyses performed by engineering designers is not brought to surface.

In an industrial survey carried out in 2007-2008 [11] within Swedish companies, answers indicated that in some companies there are activities related to this topic; about 30% of the companies let their engineering designers perform analysis. A study on the use of analysis and simulation during design (before production ramp-up) from 2006, the *Simulation-Driven Design Benchmark Report* [12]—270 companies—, made the first large attempt to clarify the companies' attitudes and strategies regarding the use of engineering designers to perform CBDA. The report established that involving the engineering designers to perform analyses was by far a minor issue compared to the other challenges of performing CBDA early. The number of companies involving engineering designers to perform analyses is not mentioned, but 29% of these companies provided easy-to-use software (CAD systems with embedded CAE for example) to their non-experts, giving an indication that around one third of the companies let their engineering designers perform analyses. This is similar to [11] , see above. The companies have also training programs in the form of tutorials, generic and specific examples, and training materials. In a follow-up study from 2013 [13], it was found that 41% of the 488 interviewed organisations captured simulation expertise to make it available to engineering designers and less experienced users; around 45% had expert users mentoring new simulation users; and analyses performed by non-experts were supported by senior management in 26% of these organisations.

Finally, research or reports on general technology development or method development were also investigated. Technology or method development, in the analysis terminology, is the development, verification and validation of specific guidelines, procedures or templates(1)for the analyst or the engineering designer to follow when performing a design analysis task [14, p. 1188]. This can be partially or fully automated. These guidelines define for example what types of meshing are allowed, what loads and boundary conditions are to be considered, what results are to be extracted and evaluated, etc. This allows for engineering designers to make some specific types of analyses while leaving more advanced analyses to the expert. Technology development or method development is present in several companies and is mentioned in [10; 12-14], but only a few papers in this

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[1] Pre-developed code that supports or guides the engineering designer in performing design analysis tasks, e.g. from predefined settings available in traditional tools, to developed in-house scripts, and advanced usage of knowledge ware.

area were found. Moreover, templates are not presented as a way of supporting CBDA. In [15], a methodology has been developed to facilitate the use of topology optimisation by engineering designers. In an industrial application reported in [16], a positive result could be achieved by introducing design analysis and optimisation to the engineering designer, all done under the supervision of a design analyst. The result from this work indicates that costs, weight, and lead time can be reduced significantly, as the engineering designer, with a little effort, might be able to evaluate a concept directly without waiting for the analyst to carry out the analysis of the concept. In two other projects [17; 18] it was shown that it was fully possible to secure quality and to configure the CAD system in a way, which confines the use of the software to those approved in advance. These two projects also shows that it is possible to support the engineering designer while performing CBDA by integrating different types of support system, in the actual case by using knowledge based systems (KBS).

3. Approach

The chosen format for this survey is that of an online questionnaire, in order to be able to reach international respondents. The survey contained a maximum of 73 questions (depending on the answers of the respondents); most of the questions were in closed format; in some of the questions, the respondents had the possibility to give additional information. The online survey tool www.quicksearch.se was used.

In order to reach relevant respondents, the following strategy was pursued. An announcement on the home pages of NAFEMS and the Design Society, and an article in NAFEMS's magazine *Benchmark* were published. To be able to reach out to those who are not members of these organisations, postings in different member groups within ASME (15) and LinkedIn (35) networks were made. Finally, a set of companies, mainly selected from an earlier survey on CBDA [11], were chosen and invited to answer the questionnaire through personal invitation. Even though there were different kinds of invitations to this survey, all respondents were handed the same information and all had the same opportunity to answer it. In the questionnaire, there was a possibility for the respondents to give their e-mail address if they were willing to answer additional questions and if they wanted feedback on the results from the survey.

The questionnaire was divided into the following eight sections linked together according to the flow chart, which is presented in Figure 1.

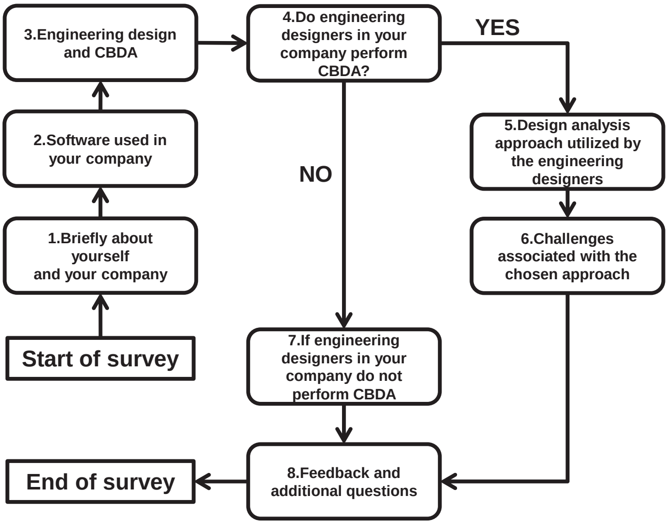

Figure 1: Flow chart of the questionnaire

1. **Personal information and information on the company**

2. **Software used in the company**

3. **Engineering design and CDBA**
   Presence of a formal product development and/or analysis process model in the company, mode of integration between engineering design and design analysis activities, use of CBDA in the different phases of the product development process.
4. **"Do engineering designers in your company perform CBDA?"**
   The question in this section directed the respondents into one of two different tracks depending on their answer.
5. **CBDA approach utilised by the engineering designers**
   Questions about how the analysis is utilised, development of methods, training, and/or support, quality assurance (QA), type of analysis performed and resources allocated for this activity.
6. **Challenges associated with this approach**
   Problems related to letting the engineering designers performing CBDA within the company.

7. **If engineering designers do not perform CBDA**
   Respondents were asked whether there are any plans for implementing this activity in the future.
8. **Feedback and additional questions**

4. Results from the survey

The total number of respondents that started the survey was 282, 77 of whom completed it. The respondents came from 71 different countries, three answers(2) came from the same company or organisation and three did not identify the company they belong to. After question 4 the survey was divided into two different tracks, see Figure 1. For sections 5 and 6 the number of respondents was 27 and for section 7 it was 50. Note that the results are sometimes presented in in form of percentage and sometimes in absolute values.

Respondent status and information about the company, section 1.

From Figure 2, the results show that the major part of the respondents were engineering designers (39%) and design analysts (27%) followed by managers (14%) and project leaders (13%).(3) The educational level of the respondents shows that most of them hold a Master's degree or equivalent education (48%) followed by 30% Bachelor's degree or equivalent and 20% holds a PhD degree, Figure 3.

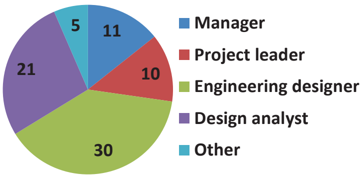

Figure 2: Primary position of the respondents

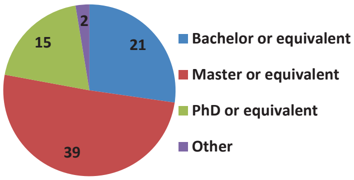

Figure 3: Formal level of education of the respondents

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[2] After examination of the respondents' answers, it was possible to discern that they belong to different analysis departments/sections within the same company; the responses have therefore been included in the survey in the same way as the responses from the other respondents.

[3] Some of the professions originally entered by the respondents in the Other category have been assessed as belonging to the main categories (for example: "FEM engineer" or "stress engineer" have been included in the Design analyst category); the presented figures have been corrected accordingly.

Compared to the Easit^2 survey [9, p. 16], these show similar numbers. In the field of experience of the respondents, it was found, Figure 4, that 67% have held their position for less than 10 years and 12 % have held it for more than 20 years. The results in Figure 5 show how the respondents were invited or how they found the survey. The respondents were invited from NAFEMS (16%), Design Society (4%), ASME (8%), and by personal invitation (21%). Most in the last-mentioned category are personal invitations from the authors of this paper. The last category was Other (52%); most of them came from different groups within LinkedIn. Overall, the respondents were employed in organisations involved in engineering consultancy (35%), manufacturing (45%), or Other (20%), as shown in Figure 6. In the Other category involves resellers, training institutes and academia.

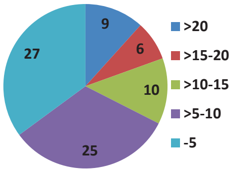


Figure 4: Number of years the respondent has been working in her/his current position

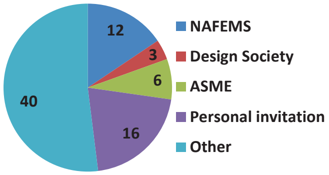


Figure 5: Engineering associations from where the respondent received this questionnaire

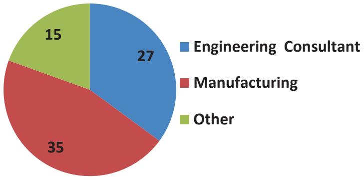


Figure 6: Type of company

The classification of the different industrial branches originates from the software manufacturer Dassault Systèmes [19]; it is similar to the classification used in the NAFEMS Simulation Capability Survey 2013 [10]. Industrial equipment (31%), aerospace and defence (23%), transportation (23%) are branches in which most respondents operate (Figure 7); these also represent branches where design analysis is often used.

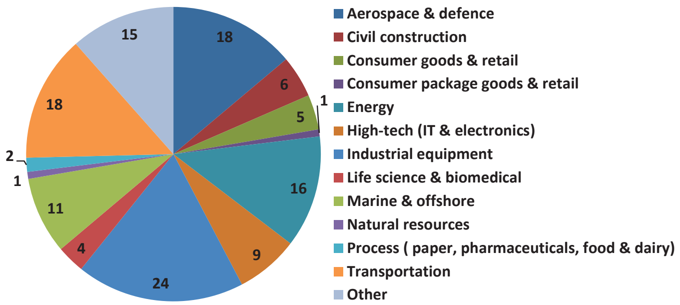


Figure 7: Industrial branch to which the respondent's company belongs

Looking at the number of employees belonging to the category engineering designers (43%), Figure 8, and design analysts (58%), Figure 9, are mainly working within smaller companies that have between 1 to 10 employees. For companies with 11 to 50 and 51 to 100 employees these categories are 22% and 17% respectively. For large companies with more than 101 employees, the numbers are 23% and 8%.

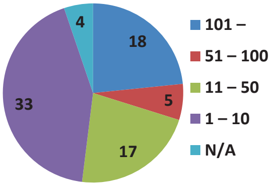


Figure 8: Number of engineering designers employed in your company

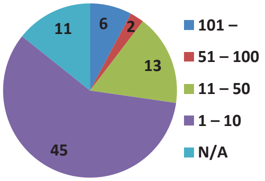


Figure 9: Number of design analysts employed in your company

Software used in the companies, section 2.

The software used for creating geometry is presented in Figure 10. Most frequently used software was: Autodesk (36%) followed by SolidWorks (34%) and Catia (30%). Additional software used was NX (21%), Pro/E, Creo (13%), and other (18%). In the Other category the respondents listed special software used for advanced surface creation and other software not listed as a special category in this survey. Least used software is Solid Edge (8%), DesignModeler (4%) and SpaceClaim (1%).

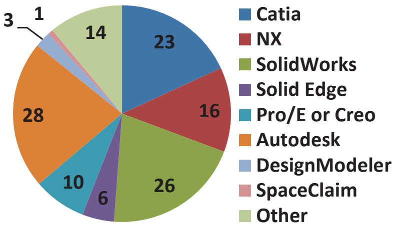


Figure 10: CAD software used in the companies

The type of software used for stand-alone design analysis and optimisation is presented in Figure 11. Structural analysis (73%) is the most common type of analysis, followed by thermal analysis (40%), computational fluid dynamics (39%), and optimisation (27%). The softwares least used are those for multi body simulation (23%), in-house developed software (25%) and other (23%). In the last two categories the respondents listed Matlab, Comsol and MS Excel. All of the top five listed software offer integrated CAE capability, and 60% of the respondents use this kind of software. KBS is also a type of support tool integrated into the most of the software used. There is a low usage of this type of software. Only 10% of the respondents report that they use some type of KBS, and 88% of them use the CAD-integrated KBS.

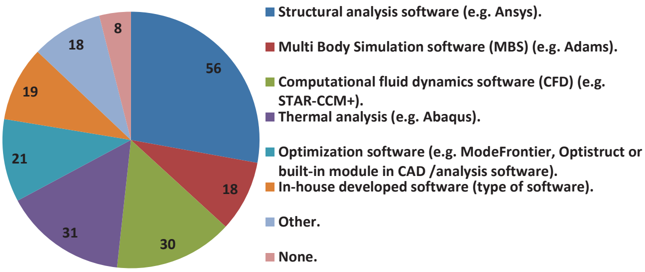


Figure 11: Stand-alone design analysis and optimisation software used for analysing products

Engineering design and CBDA, section 3.

In the literature within engineering design and design analysis, process models for each of the two categories are fairly well described. However, the integration between these two types of processes is much more difficult to find [11; 14]. The majority of the respondents answered that they utilise a formal engineering design process model (44%), see Figure 12, but 27% were using a formal CBDA process model—see Figure 13. When it comes to fully integrated process models, Figure 14, 21% answered that they use an integrated CBDA process models. A large number of respondents (37) answered the question by N/A. This might indicate that they the respondents did not know either whether their company had any integrated process model or that they did not understand the meaning of the concept of integration in the given context.

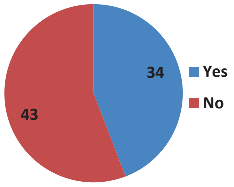


Figure 12: A formal engineering design process model is utilised

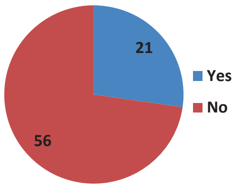


Figure 13: A formal CBDA process model is utilised

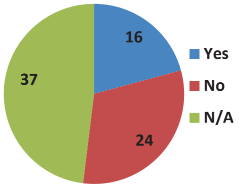


Figure 14: The engineering design process model and the CBDA process model are integrated

Figure 15 shows the percentage of the design analysis activities the companies perform in all the different phases of the product development process.The average results are presented in Figure 16 and compared to the NAFEMS Simulation Capability Survey 2013 [10].The results are quite similar and indicate that the companies that answered the present survey are representative. The relatively large usage of CBDA in the manufacturing phase can be explained by the fact that the manufacturing of production equipment is a part of this phase. In the Other category, respondents have put elements such as analysis for solving problems outside a product development project, failure analysis of returned parts and for analysing deviations, while in [10] the Other category was primarily chosen by respondents who were using the capabilities for methods development or other research activities. By cross-tabulating the data, it could be found that of the 27 respondents who answered that they utilise an integrated process, 10 of them involve their engineering designers to perform design analysis.

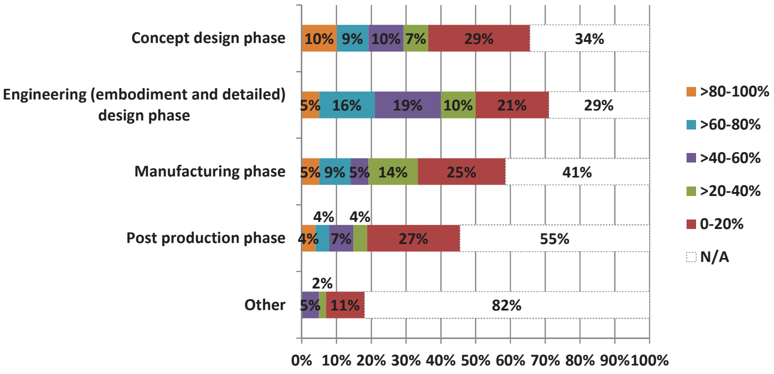


Figure 15: Distribution of the analyses performed over all development phases (read: 10% of the companies spent 80 to 100% of their analysis capabilities in the conceptual design phase)

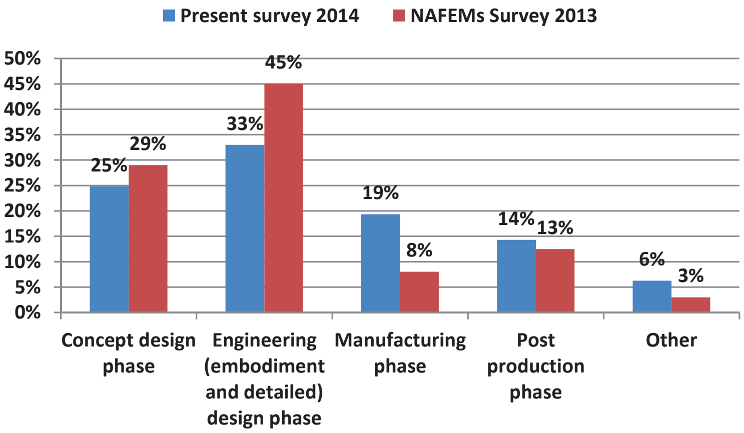


Figure 16: Comparison of the present survey with the NAFEMS Simulation Capability Survey 2013 [10]

Do engineering designers in your company perform CBDA? section 4

To that question, 35% answered that their engineering designers perform design analysis (Figure 17). This is similar to the figure from the Aberdeen reports [12; 13], mentioned in the Related Work section. From those that answered no (65%), the reasons for which the engineering designers do not perform CBDA were that they do not have any projects that are suitable for this activity, or it is a policy within the company that all design analysis should be performed by an analyst. These respondents were further asked whether they planned to implement such an approach in the future. These results are reported section 7.

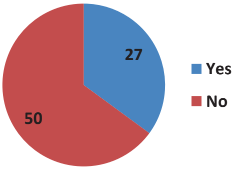


Figure 17: Do engineering designers in your company perform CBDA?

CBDA approach utilised by the engineering designers, section 5

The respondents were asked to assess the value of the advantages obtained by letting engineering designers perform CBDA on a 5-point rating scale. The results are presented in Figure 18. The average score for each advantage is as follows: to allow early evaluation of concept candidates (4.0), frees resources for the analysis department (3.9), shortens lead time (3.6), to facilitate an evaluation of additional concept candidates (3.5), to facilitate a more extensive generation of concept candidates (3.3), economical reasons (2.6) and to limit the use of engineering consulting companies (2.4).

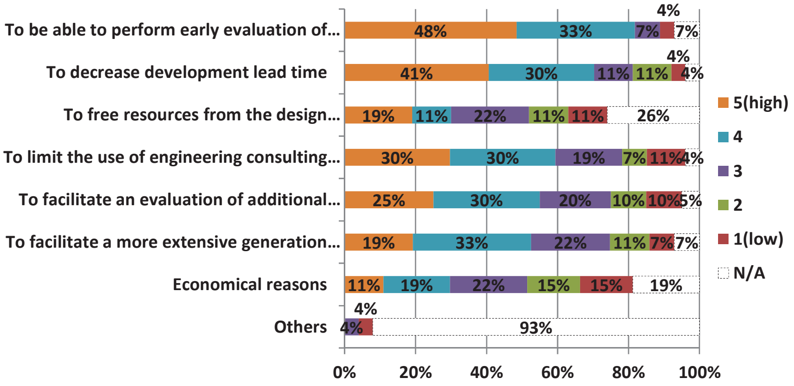
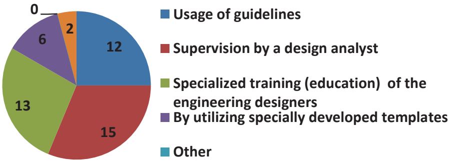


Figure 18: The advantages obtained by letting engineering designers perform CBDA

The companies that allow the engineering designers to perform CBDA have a plan for supporting and training their engineering designers. Supervision by a design analyst (56%) and special training (48%) is the support that is used most frequently, see Figure 19. Even though the engineering designers receive support while performing CBDA, it is important to secure the quality of the analysis performed. Most of the companies have some sort of quality assurance approach: control by a design analyst (59%), followed by specialised guidelines (37%), see Figure 20.



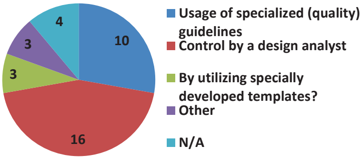


Figure 19: Types of CBDA supports for the engineering designers

Figure 20: Quality assurance for the results of CBDA performed by the engineering designers

Figure 21 delivers an interesting result. The development of the CBDA approach is mainly done within the company, and it is done in cooperation between the engineering design and design analysis department.

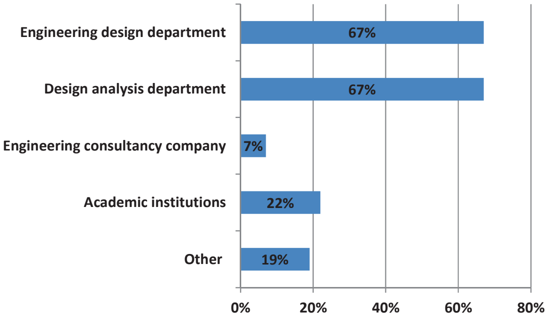


Figure 21: Responsibility for developing the CBDA support(s) for the engineering designer

67% answered that they only deliver a basic level of support during the analysis activity for their engineering designers, while 41% answered that they utilise a semi-automatic level of support, Figure 22. Among the different targeted analysis types for which a CBDA support for engineering designers has been developed, linear static (85%) is the most frequent one, followed by non-linear analysis (52%). CFD (41%), thermal (37%), dynamic (37%), and optimisation (33%) also have CBDA support for engineering designers, see Figure 23.

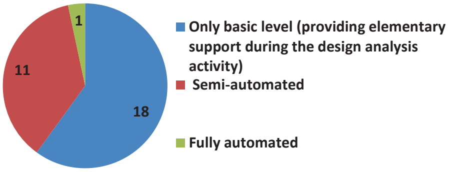


Figure 22: Automation level built into the CBDA support for engineering designers

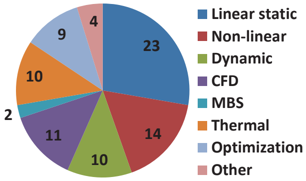


Figure 23: Usually targeted types of design analyses with CBDA support for engineering designers

Validation and verification (V&V) is used for the CBDA approach supports in all cases. Verification is the assessment of the accuracy of the computational model of the design solution, and the validation is the assessment of the accuracy of the simulation results by comparison to data from reality by experiments (by means of prototypes) or physical measurements in working environments. Most frequently used is physical testing and comparison with field data (67%), which corresponds well with the findings in [11], followed by reviews by an expert (56%) or by using different resources within the company (41%). Only 15% answered that they use external resources for the V&V, see Figure 24. Two respondents answered that they do not use any V&V (category Other). It is interesting to note that there seems to be increased engagement in verification from other resources in the company and thus not relying on analyst individual responsibility as found to be the case in about 44% of the companies interviewed in [11].

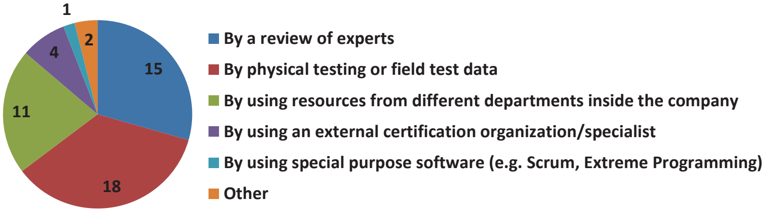


Figure 24: Verification and validation of the results of CBDA performed by the

engineering designers

Built-in support for the interpretation of the results is used by 44%, see Figure 25. For this activity, special guidelines and/or instructions (67%) or post-processing calculations on established results based on applied rules (58%) are utilised, see Figure 26.

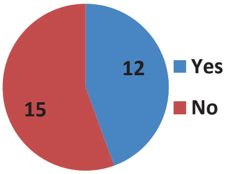


Figure 25: Built-in support (during or after post-processing) for the interpretation of the results of CBDA performed by the engineering designer

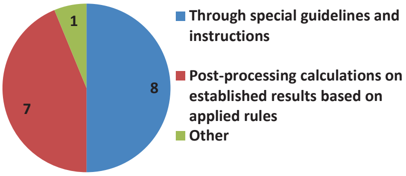


Figure 26: Interpretation of the results of CBDA performed by the engineering designer

How the companies divide their activities between engineering designers and design analysts usually depends on what type of design analysis is to be performed. The complexity of the design analysis task (78%) and the type of design analysis (67%) are the factors considered for the allocation of the design analysis activities, see Figure 27.

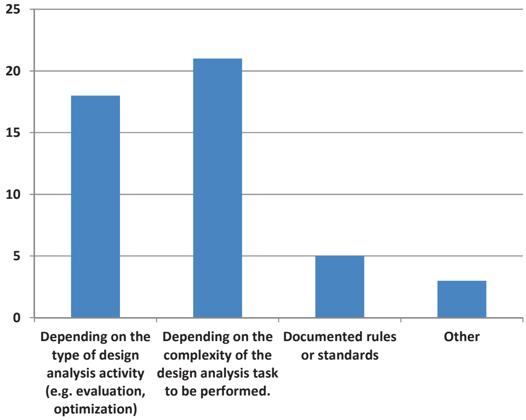


Figure 27: Grounds for allocating design analysis activities between the engineering designers and the design analysts

From this survey it is obvious that the design analysts have an important impact on the CBDA supports for the engineering designers. When preparing the engineering designers for the use of design analysis, 74%, compared with 61% from the Aberdeen Group report from 2013 [13], answered that support from the design analysts is most frequently used, and 33% of the respondents answered that special training had been developed for this purpose, see Figure 28.

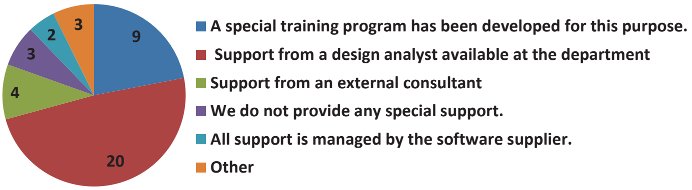


Figure 28: Preparations for the engineering designers to perform design analysis on their own

In Figure 29 the results show that physical testing and/or advanced simulation by a design analyst is the most common approach for validating the result from CBDA performed by engineering designers (76%).

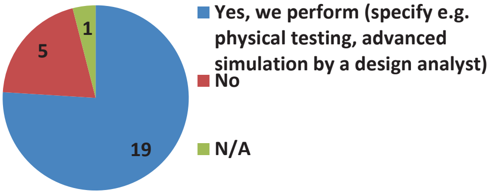


Figure 29: Measures taken to control the results obtained from the CBDA performed by the engineering designers

Challenges associated with the chosen approach, section 6

Implementing CBDA is not an easy task. There is always some problem that has to be solved, Figure 30. The most frequent problems are hardware and software issues (30%), resistance from the design analysis department (26%), and resistance from the engineering designers (19%). 26% answered that they have not met with any problems. Two respondents also answered that KBS is something not many coompanies understand or do not know how to use.

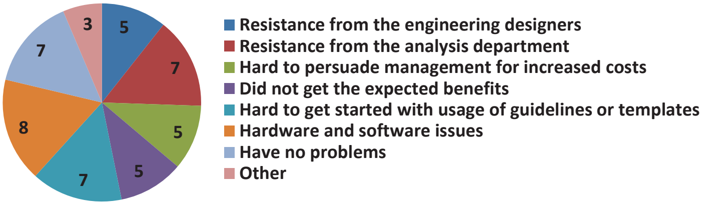


Figure 30: Experienced problems when developing and using the CBDA supports for the engineering designers

Companies without CBDA support for their engineering designers, section 7

For those who answered that their engineering designers do not perform design analysis (65%, see Figure 17), 28% have future plans to implement CBDA for their engineering designers, see Figure 31. They will implement CBDA for their engineering designer as they see an advantage in: higher productivity, shorter lead-time and cost savings. Some of the arguments put forward by the respondents who do not plan to implement CBDA support for their engineering designers, were that, among other things: the engineering designers did not possess enough knowledge about CBDA, management did not see any benefits, it was not required for the company’s projects or the projects were to small, or the workload of their engineering designers was already too high.

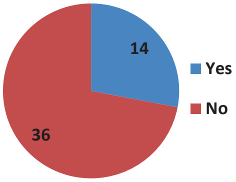


Figure 31: Future plans to implement CDBA supports for the engineering designers

Feedback and additional questions, section 8

The questionnaire ended with some questions requesting feedback from the respondents on the questions in the survey, whether they wanted to be sent the results and whether they were willing to answer additional questions. 62% answered that they wanted direct feedback on the results of the survey, and a surprisingly high percentage (54%) answered that they were willing to answer additional questions.

5. Discussion and future work

About the survey approach

The number of respondents can be considered as quite low (77), given the call for participation was made through many different channels (most responses came from LinkedIn and their member groups.) However, the respondents were members of NAFEMS, belonged to professional analysis groups, or were personally invited, so the respondents can be considered as knowledgeable in the field of inquiry. Moreover, among those who have responded, 77% came from the industrial equipment (31%), aerospace and defence (23%) and transportation (23%) sectors, which have extensive use of design and design analysis. Also, for the questions asked in other surveys, such as the NAFEMS Simulation Capability Survey 2013 [10] and the Aberdeen reports [12; 13] the answers had similar rates (see Sections 1 and 3). The answers can therefore be considered as sensible and reliable.

About the survey results

First and foremost, this survey establishes that 53% of the companies have introduced or plan to introduce CBDA for their engineering designers, a very high number. The results from the survey show that there are possible savings in lead time, opportunities to generate additional concepts and lower costs. It is also interesting to see that, in some of the groups where the survey was posted, there are discussions in progress regarding this subject, and the majority of the respondents are willing to answer additional questions. This shows the broad attention this subject has attracted from the community.

At the same time, relatively few academic works have been published on the subjects. There are several challenges to address, such as cultural changes (resistance from the engineers and analysts), need for training… Regarding education, it might also be necessary to ensure that design analysis is given sufficient attention in engineering design education programs. Training of engineering designers pointed out as a main challenge in the NAFEMS FENet survey of 2005 [20], see also [21].

One specific aspect that also requires further investigation is the potential benefits from the use of templates. Templates present the possibility to control quality in the work of the engineering designers without the constant involvement of expert analysts, but developing them requires resources. This and other related challenges are therefore to be taken up in a follow-up survey, to be released in late January 2015. It will be addressed to the respondents of this survey who accepted to answer further questions as well as new invited companies.

Raw data from the present survey are available upon request.

Future work

The survey revealed many interesting answers as presented in this paper but there are still questions that need to be further investigated. For example, the reasons behind the large resistance to the use of CBDA (26% of the design analysts and 19% of the engineering designers) need to be investigated. In the follow-up survey mentioned above, focus is set on getting fine-grained knowledge about the subject of letting the engineering designers perform CBDA, mainly in terms of gained collaboration, cost savings, shorter lead times and on the types of support required in the different product development phases (especially templates). Of those 54% that answered that they are willing to answer additional questions, 56% answered that they do not let their engineering designers perform CBDA; it might be interesting to see if this number has changed between the two surveys and, if so, what the reasons behind it might be. The survey will also be complemented by personal interviews in targeted companies.

6. Acknowledgments

The authors wish to express our gratitude to the respondents for their participation in the survey.

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Paper IV

A process model for enhanced integration between computer-based design analysis and engineering design

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A process model for enhanced integration between computer-based design analysis and engineering design

The findings from a survey in industry and from an extensive literature survey revealed the need for the development of an integrated process model for computer-based design analysis (CBDA) facilitating the interactions in the engineering design process in mechanical engineering on an operational level. CBDA is here confined to the utilization of advanced computational methods and tools from computer aided engineering (CAE), such as computational structural mechanics (CSM), computational fluid dynamics (CFD) and multi-body systems (MBS). In order to facilitate integration to the multitude of engineering design process models in industrial practice, including overall processes such as product innovation and product development, the process model needs to be adaptive and generic. Generic should here be interpreted as not being dependent on any specific type of product, engineering design process, or on any specific type of product innovation and/or product development process models utilized by an enterprise. Resulting from synthesis processes based on the findings from surveys and experiences gained from design analysis projects in industrial practice, the generic design analysis process (GDA) model was developed. The application of the GDA process model is exemplified by four examples, which have been utilized for validation of the process model.

Keywords: generic design analysis process model, computer-based design analysis, engineering design, integration, workflow

1 Introduction

During recent decades the rapid development of computer-based design analysis methods and tools has fundamentally affected the way in which products are designed and developed. The implementation of these methods and tools into industrial practice is here referred to as computer-based design analysis (CBDA) or design analysis for short - as long as this abbreviation is unambiguous. Design analysis can take a multitude of forms including methods and tools of both a qualitative and a quantitative nature. Here, design analysis is confined to quantitative analyses, utilizing advanced, computer-intensive computational methods and tools focusing on analyses of those physical phenomena, which originate from the design and development of new or improved products or from redesign of existing ones. The products (artefacts) referred to here are those resulting from an industrial manufacturing process and based on one or more working principles of mechanical origin.

A prerequisite is that the physical phenomena are computationally solvable with current state of the art computer aided engineering (CAE) methods and tools, such as computational structural mechanics (CSM), computational fluid dynamics (CFD) and multi-body systems (MBS). CSM is a common denominator for methods and tools applicable for structural analysis including the finite element method (FEM), the boundary element method (BEM) and meshless methods such as the element-free Galerkin (EFG). In industrial practice, the CAE methods and tools are frequently utilized together with different complementary techniques such as design of experiments (DOE), knowledge-based engineering (KBE), optimization (by methods such as approximation methods, evolutionary algorithms and gradient based methods for e.g. size, shape and form and topology optimizations performed as single- or multi-objective as well as single- or multi-disciplinary).

Since the design analysis process, on an operational level, is confined to design tasks derived from the engineering design process or from engineering design related activities emanating from pre-product development activities, it is necessary to already here briefly elaborate on these activities and processes. Product development in its industrial setting is here regarded as a multifunctional process which includes, as a minimum, the following sub functions: marketing, design and production (Andreasen and Hein 1987; Ehrlenspiel 1995; Olsson, Carlqvist, and Granbom 1985; Ulrich and Eppinger 2012); in the academic setting multifunctional is often substituted by multidisciplinary.

The single most important sub function in the development of physical products is design. Design, on the other hand, in the industrial enterprise is often divided into two major areas: industrial design and engineering design. In the given context the focus is on the engineering design process, as the majority of design analyses tasks are performed during this process. The pre-product development activities referred to above are mainly derived from the product planning process, during which synthesis oriented activities dominate. Especially, the possibility to explore a design space for new concepts and verify the expected performance of proposed concept(s) as a part of evaluating them constitutes important engineering design activities during this process. Also in the production process, subsequent to the product development process, the engineering design process is utilized e.g. in the design of production equipment such as design of fixtures and production cells.

The significance of the design analysis process within the engineering design and product development processes is well established. In the NAFEMS Simulation Capability Survey 2013 (Newton 2013), the results from 1115 respondents show that design analysis is now used in all phases of a product development project, with 30% of all analyses performed during the conceptual design phase. In order to extend the utilization of design analysis in industry, engineering designers have taken over parts of the design analysis process.

The use of design analysis introduces a number of specific issues. Design analysis is usually performed by a specialist, the design analyst (or analyst for short), employed by either the enterprise or an engineering consulting enterprise. Since the analysts and engineering designers work with, and are responsible for, different areas, they do not necessarily have full insight into each other’s way of working. They are also utilizing different software, and compatibility problems are frequent. The issue of integration between the design analysis and the engineering design process is, in other words, of major significance for providing an increase in efficiency and effectiveness in engineering design and development of products as well as for the engineering designers’ prospects in the future to more actively participate in the design analysis process. A similar increase in efficiency and effectiveness of the design analysis process is expected, together with increased understanding of the nature of engineering design by the analyst.

In sixteen reviewed textbooks, among others by (Dieter and Schmidt 2013; French 1998; Haik and Shanin 2010; Otto and Wood 2001; Ullman 2010), design analysis is not emphasized in the process models. In the few cases where it is mentioned, e.g. Ehrlenspiel (1995), the German versions of Pahl and Beitz (2007), and the VDI guideline

2221 (VDI 1993), it is only considered as a part of the verification of the product properties and described in a non-operational manner.

From the findings described above, there is an apparent need for the development of an integrated process model facilitating the interactions between the design analysis and the engineering design processes on an operational level. The need for such a process model is not confined to industrial practice but is also of major importance for the training of new generations of analysts and engineering designers. Even though many enterprises have adopted product innovation, product development and engineering design process models based on textbook literature and on additional publications for their development and design processes, these are mostly adapted to fit the specific conditions of the individual enterprise and thus deviate significantly from the original textbook models. This implies that the required process model also needs to be both adaptive and generic, here to be interpreted as not being dependent of any specific engineering design process model and of any specific type of product. The process model should also facilitate the integration between the design analysis and the engineering design processes on an operational level corresponding to that of the constitutive activities of the design analysis process.

The development of such an integrated process model is reported in this paper. Applications of the proposed process model to some specific engineering design related tasks, frequently occurring in industrial practice, are elaborated upon and exemplified. The findings from these applications of the process model are presented in the concluding remarks, together with some suggestions for the future development of the proposed process model.

2 Research approach

The research work presented here is the result of a synthesis process based on the results obtained during a number of individually performed, but conceptually linked, research projects. The start of the research efforts dates back to 2007, when an explorative survey was performed in Swedish industry on the integration between the design analysis process, the CBDA process, and the engineering design process.

The reason for beginning with an explorative survey in industry was simply the fact that design analysis in industry is performed on a regular daily basis and on an operational level which of necessity also includes some form of integration between the design analysis and the engineering design processes. The survey results were, in other words, expected to provide a fairly complete picture of the interactions between the processes in industrial practice, as no such integrated process model was to be found in the literature. The survey was thus expected to provide essential results comprising the possibility to find integrated process models in industrial practice not generally known, as well as provide essential information necessary for the development of such a process model.

Simultaneously with the survey in industry, an explorative literature survey was performed with almost parallel goals, to extract all possible information on integrated process models and of research results of importance for the development of such a process model. Both surveys were extremely time-consuming and the results were therefore not fully documented and published until 2014 – see (Eriksson et al. 2014; Motte et al. 2014).

The results obtained during the surveys, presented in chapter 3, were utilized in a first synthesis phase for the development of an initial integrated design analysis process model (Eriksson and Motte 2013a), together with an account of a number of factors influencing such a process in industrial practice (Eriksson and Motte 2013b).

In the final phase of the research work, all results were brought together in a synthesis procedure resulting in the generic design analysis process model – the GDA process model. During the industrial survey, four frequently occurring categories of analysis situations were identified. For each of these, embryos for adapted versions of the workflows in the GDA process model were developed and exemplified.

3 Point of departure

Given the objective for the research work presented here, there is a need for investigating existing design analysis as well as engineering design process models which fully or partly fulfil the goals of an integrated process model, or can be utilized as a foundation upon which such a process model can be built. It is also necessary to investigate the interaction between the engineering design process and the overall product development process and in turn between the latter and the other processes involved during design, development and materialization of a product, such as product planning and production processes. In order to give as complete as possible an understanding and account of the interactions between all of these processes, it is here also necessary to introduce the product innovation process. In addition to the focus on processes, it is equally important to investigate and explain the nature of integration as a means for the development of an integrated process model. Integration is, in other words, a cornerstone in the building of a process model that enables the necessary exchange of data and information on an operational level as well as ensuring the flexibility to adapt to different conditions and products, and thus also to the generic nature of such a process model.

3.1 Engineering design process models in an overall process perspective

Since the introduction of Newtonian mechanics, extensive efforts have been put into the development of efficient and effective engineering design process models for mechanical engineering design, beginning in Germany already in the mid-19th century in the works of Redtenbacher (1852) and Moll and Reuleaux (1854).

One of the most prominent of current process models, and probably the one which still today has had the most fundamental impact as a theoretical foundation upon which a significant number of current engineering design and product development processes models are developed, is the engineering design process model by the German professors Pahl and Beitz. The process model was first introduced in their book *Konstruktionslehre* in 1977 (Pahl and Beitz 1977); in English *Engineering Design – A systematic approach*. The book originates from a series of articles in the German journal *Konstruktion* denoted “Für die Konstruktionspraxis”, in which other German professors as Roth and Rodenacker participated as co-authors (Pahl and Beitz 1972-1974). At the time, numerous publications on engineering design were also published by other German researchers and engineering organizations, among others by Hansen (1968; 1974), Hubka (1973; 1976), Koller (1976), Rodenacker (1966), Roth (1982), and by the Association of German Engineers (Verein Deutscher Ingenieure, or VDI) such as the VDI guideline 2222 Part 1 - *A systematic Approach to Conceptual Design* (VDI 1977), but also in other countries as in the UK by

Glegg (1972), French (1971) and Jones (1963; 1970), in the US by Asimow (1962) and the famous *Shigley's Mechanical Engineering Design* which, after nearly 50 years, is still being updated by new editions (Budynas and Nisbett 2015), and in Sweden by Jakobsson and Sundström (1960). Gradually, the different systematic engineering design process models have adopted a common ground, and they differ only in peripheral variations (Motte 2008).

An operational interpretation of the nature of engineering design adopted here is to consider engineering design as a process starting from a predefined setting that might range from a material need to a well-defined technical solution or principle ending up in a set of documents utilized for the materialization (production) of the product-to-be. During this process a number of iterative synthesis-analysis-evaluation loops are carried out.

Examples of product development process models in which the engineering design process model is embedded are found in Olsson, Carlqvist and Granbom (1985), Andreasen and Hein (1987), Pugh (1990), Ullman (2010) and Ulrich and Eppinger (2012). In some of the product development process models, product planning is considered to be the initial phase of the development process, e.g. in Ulrich and Eppinger (2012). Here product planning is regarded as an independent pre-product development process. Product planning might briefly be described as a process during which an input in the form of incentives for development of fundamentally new products, development of derivatives based on existing platforms, development of new platforms and improvements of existing products are transformed into a project portfolio consisting of well-defined, prioritized (in time), product development projects. A number of more or less detailed process models are presented in amongst others (Ulrich and Eppinger 2012; Olsson 1995; Wheelwright and Clark 1992).

Even though additional ways of structuring the product development process exist, the process models derived from an embedded, generic, engineering design process model are adopted here as a role model for the integration of design analysis (CBDA) and engineering design. This decision is based on the fact that, in the given context, the essential integration is confined to technical aspects of the (physical) product-to-be or to the re-design of an existing product.

To summarize: As previously noted, in none of the process models accounted for in this section is design analysis integrated on an operational level. However, in the majority of the PD process models, integration between their constitutive sub-processes and their sub-activities or steps are fully developed (at least in theory), which reduces the integration problem to that between the engineering design process (ED process) and the engineering design activities (ED activities) and the design analysis process. The sequential linking of product planning (PP), product development (PD) and production (PN) defines the overall product innovation (PI) process; even though the PI process thus might be regarded as simply a "label" it is essential to specify it due to its role in the overall enterprise perspective. All of the processes are illustrated in Figure 1. The actual contents in the form of the sub-activities or steps forming the ED processes and the ED activities in each of their overall processes can be identified as long as the actual process models are known in detail, which is seldom the case in industrial practice and thus no attempt has been made here to introduce such content.

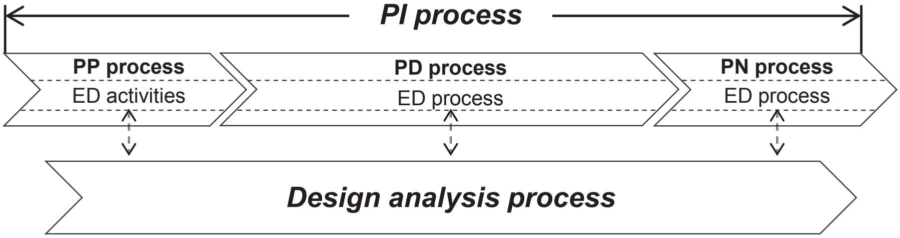


Figure 1. The interrelation (dashed arrow) between the PI process and the design analysis process, including the sub-processes of the PI process and the ED processes and the ED activities.

3.2 Design analysis process models

When numerical design analysis methods such as FEM were introduced for a broader audience in academia and industry, the main focus was how to solve established numerical problems accurately and efficiently by utilizing a number of procedures, methods and techniques. Such analysis procedures can be found in works by Bathe (1996), Belytschko et al. (2014), Chopra (2012), Cook (1995), Cook et al. (2002), Fish and Belytschko (2007), Liu and Quek (2003), Ottosen and Petersson (1992), Zienkiewicz and Cheung (1967) and Zienkiewicz, Taylor and Zhu (2005) just to mention a few of the vast variety of publications on FEM. Procedures on BEM can be found in e.g. Brebbia and Dominguez (1992) and Mukherjee and Mukherjee (2005) and meshless methods can be found in e.g. Belytschko, Lu and Gu (1994) and Liu (2003).

The analysis process model by (Bathe 1996) starts from a predefined physical problem that is translated into a mathematical model, which in turn is translated into a solvable finite element analysis (FEA) formulation. Resulting from the solving/execution of the FEA problem, the results undergo an assessment of the accuracy (verification) of the mathematical model. If the result of this investigation is satisfactory, the results are interpreted and downstream activities such as design improvements and/or optimization follow.

With the further development of software and generalization of the use of such numerical methods, process models have been gradually developed that encompass industrial aspects in order to support the practitioner's work (Adams and Askenazi 1998; Gokhale et al. 2008; Moaveni 2014; Rao 2005; Sunnersjö 1992; Zahavi 1992). NAFEMS (originally the National Agency for Finite Element Methods and Standards) has proposed several models during the last few decades that are intended for practical implementation in industrial practice.

In *How to Plan A Finite Element Analysis* (Baguley and Hose 1994), the workflow of design analysis tasks includes steps that couple analysis to the development project: it includes for example tasks that are project- and enterprise-related: preparation and agreement of specification of the task, preliminary calculations in order to provide resource estimations, etc. The workflow is concluded with information feedback in terms of presentation and reporting.

Even if design is mentioned in Bathe's process model, the main objective behind the process models presented above is to introduce analysis process models as such and not design analysis. However, process models that could be characterized as genuine design analysis process models were also found in what during the literature survey (Motte et al. 2014) was referred to as design analysis literature. These process models are also fairly similar in their decomposition into phases, but differ when it comes to the individual steps or activities forming up each of their phases (Motte et al. 2014). Adams and Askenazi (1998) discuss the basic steps of solving engineering problems, and they emphasize the importance of establishing a clearly defined goal and of determining the level of uncertainty in the technical specifications. Furthermore, they also highlight the importance of establishing an appropriate mathematical model, since the predictions of the FEA-results are limited by the assumptions made on the majority, if not all, of the input parameters of the mathematical model.

To summarize: As previously mentioned, the process models presented above provide a decomposition of the analysis process into three common and clearly distinctive phases: analysis planning, execution (also denoted solution processing) and result interpretation and communication. Each of these phases encompasses a number of activities or steps that to a large extent are common in nature, but diverge depending on the overall perspective adopted for the structuring of the process model under examination. Both the analysis and design analysis literature contain a number of more or less common activities or steps suitable for implementation in a generic design analysis process model. In Figure 2 the interactions between the design analysis process and the ED activities and the ED processes are illustrated. It should be noted that these interactions cannot be elaborated upon in any detail before the actual activities/steps are fully known on both "sides" of the interaction arrow.

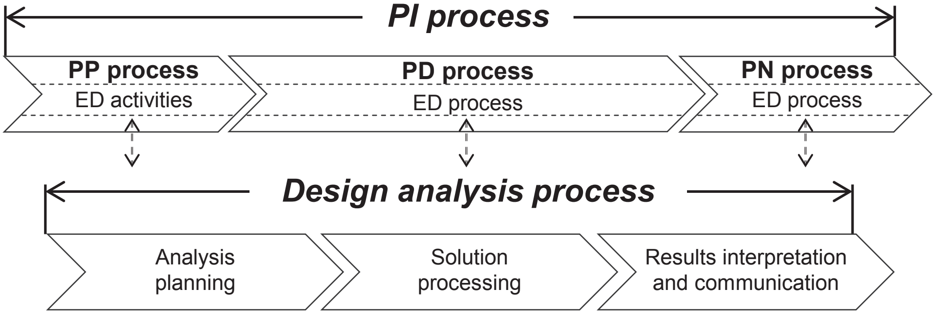


Figure 2. Illustration of the main phases of the design analysis processes and its interactions (dashed arrow lines) to the ED activities and the ED processes.

3.3 Integration

The main focus here is to provide for an efficient and effective integration, on an operational level, between relevant activities within the engineering design and the design analysis processes. Note that the interactions between the ED activities and ED processes and the other activities within and between the PP, PD and PN processes are already at hand due to the integrated nature of these processes - see section 3.1. Integration of this nature is usually referred to as integration on an organizational level, which can be described as being "the quality of the state of collaboration that exists among departments that are required to achieve unity by the demands of the environment" (Lawrence and Lorsch 1967; as cited in Andreasen, Hansen, and Cash 2015, 86).

In a comprehensive literature survey by Burman in 1993 (Burman 1993), 306 monographs and 225 articles were reviewed. The result revealed that although many authors called for a better integration of design analysis into engineering design, works in that direction were in effect very limited. Only 18 publications and 2 monographs were found to couple design analysis and the engineering design process. An equally disappointing result was found in the literature survey carried out by (Motte et al. 2014), in which the objective was to present a systematic review of the works from the literature on engineering design methodology and design analysis covering the integration of the design analysis process into the engineering design process.

From the literature survey (Motte et al. 2014) it was found that design analysis was mentioned in Pahl and Beitz (2007) in a specific chapter on computer-supported engineering design where computer-based tools are introduced in their general engineering design process model. The part concerning design analysis is not detailed, and is mostly descriptive. This chapter has been re-written in all subsequent editions but has never been integrated in the main chapters dealing with the synthesis activities of engineering design. This chapter was not included in the English translations (except in the first one, Pahl and Beitz 1984). The VDI guideline 2211 Part 2 (VDI 2003) provides recommendations on the use of design analysis within the engineering design process model presented in VDI 2221 (VDI 1993). To conclude, the literature on engineering design and product development is, with a few exceptions, focused on synthesis aspects of engineering design rather than on design analysis, and thus no information on the actual integration mechanisms between design analysis and engineering design can be found. According to Birkhofer (2011), this is going to continue: "the worlds of Design Methodology and CAX technologies, with its models and procedures, increasingly draw apart" (9).

As mentioned in Section 3.2, the number of publications on design analysis is extensive, ranging from fundamental research on design analysis methodology and technologies to recommendations on the use of design analysis for specific purposes as well as on generic design analysis process models. The design analysis community has, in other words, mainly focused on the analysis task as such with the intention of providing means for supervising and increasing its effectiveness but neglected its interaction with specific engineering design tasks, which are merely seen as input and output of a design analysis project.

In an industry survey from 2003 including five companies by (King, Jones, and Simner 2003), a framework for integration of CAE into product development in order to develop faster, more economically and to a higher quality is discussed and referred to as a "good practices model". The findings were summarized and expressed in terms of five areas that need to be addressed in order to achieve an effective CAE analysis implementation: 1) the organization of the product development process, 2) software, 3) hardware, 4) support structures for effective use of CAE in the product development process and 5) product data management.

As noted by Fahey and Wakes (Fahey and Wakes 2005), general discussions about integration must be completed with practical guidelines. There are in effect several shortcomings regarding the traditional interaction models between the simulation and the engineering design activities.

Some practical guidelines dealing with planning can be found in Anker (1989), and in Tyrrell (1993). Most interesting, from an integration point of view, is the acknowledgement of computational and manpower resources availability that emphasizes also the inherent importance of involvement of the enterprises on a broader sense to facilitate successful implementation and utilization of design analysis within any given project.

Already in 1987, Gant (1987) exposes that the main issue for integration of computer-based design systems into the engineering design process is the user friendliness and compatibility of the different systems (CAD, FEM, etc.). For Clarke (1987), an integrated process necessarily must provide for software integration where many of the skills of the design analyst are incorporated within the software. Importantly, Melchinger and Schmitz (2003), Albers and Nowicki (2003) and Meerkamm (2011) discuss the use of different tools and methods in the different phases of the engineering design process, where MBS and FEA as well as topology optimization are recommended already at the conceptual design level, and shape optimization at the detail design level (Albers and Nowicki 2003) depict the ultimate goal of such integration, sometimes called simulation-driven design (Sellgren 1999) or simulation-based design (Shephard et al. 2004).

Numerous publications have since been focusing on this software integration at various levels: interoperability at feature level; CAD to CAE feature simplification and idealization (Dabke, Prabhakar, and Sheppard 1994; Stolt 2005)); CAE to CAD reconstruction (Belaziz, Bouras, and Brun 2000; Lee 2005); new shape representation (Hamri et al. 2010), at a higher information level (Bajaj, Peak, and Paredis 2007a; Bajaj, Peak, and Paredis 2007b; Dolšak and Novak 2011); or a complete integration in software packages such as PTC's Creo Parametric, ANSYS Workbench environment, Dassault Systems' Simulia portfolio, Altair Hyperworks, etc. A survey within the area was conducted by (Bianconi, Conti, and Di Angelo 2006) that concluded that interoperability among CAD/CAM/CAE systems is mostly related to information loss and incompleteness during data exchange. This has also been given attention in studies of engineering IT systems supporting the communication and management of information among various stakeholders. The context has been to provide new architectures (Burr et al. 2005).

Thanks to increased software integration, the traditional frontier between design synthesis and design analysis that has been prominent in engineering design (Pahl et al. 2007)has become less distinct. This has facilitated an approach to integration through automation of parts of the design process. Many works on formal design synthesis (Antonsson and Cagan 2001; Cagan et al. 2005) have devised programs that solved specific design problems. One motive for this approach is that it allows the development of concepts that would not be possible to obtain via a more classical investigation (Parmee and Bonham 2000). Nordin et al. (2011) have developed a generative design system for a bookshelf whose structure is based on Voronoi diagrams; the structure evolves with help of evolutionary algorithms and concepts, and at each generation step potential solutions were evaluated for structural soundness and stability through FEM. Other motives are the decrease in time and resources it allows, the possibility to have a coupled expert system, etc. In Petersson et al. (2012), a computer-based design system for lightweight grippers has been developed that can be used by production engineers who possess very limited knowledge and experience of design and analysis.

Additional aspects of an integrated process model are the fact that management of design analysis has also become more complex; design analysis is now of the utmost importance to quality assurance in product development in sensitive areas such as the automotive, aeronautical and defence industries. Certain analysis methods are dictated by the enterprise, by standards, regulations or by specific organizations; for example, analyses in the offshore industry are often quality-checked by a third-party independent evaluation such as DNV GL (formerly Det Norske Veritas and Germanischer Lloyd) or Lloyd.

To summarize: There are presently no fully integrated process models linking the engineering design and the design analysis processes available in the literature on engineering design and product development or in the literature on design analysis. Regardless of this lack of theoretical support, different forms of integration are practiced daily in industrial practice, as shown above. The problem of integration becomes even more complex when considering that such a process model must not only handle all procedural issues on an organizational level but also needs to be adaptive on an operational level in order to be linked to the different process models utilized in industrial practice. Since the structural decomposition of design analysis models is mainly governed by the generic phases accounted for in section 3.2, a generic design analysis process model is the best platform to secure integration between the design analysis process and the ED activities and ED processes on an operational level.

4 The generic design analysis process model – the GDA process model

Originating from the information obtained during the literature survey (Motte et al. 2014), a number of design analysis process models were identified in section 3.2 as being of interest for the synthesis of a first version of the GDA process model. In addition to these process models, additional elements in the form of specific activities, methods, practices, techniques and tools were identified as candidates for being incorporated into the process model; special attention was given elements related to quality assurance (QA), verification and validation (V&V) and uncertainties. The sources of these elements originated predominantly from the literature survey and the findings from the survey in industry, presented in section 3.1. Another source of information, denoted as “best practices”, originates from more than 10 years of personal experience of the main author’s work in a consulting enterprise with design analysis projects within the domains of automotive, offshore and aerospace industries. Utilizing this kind of knowledge might be regarded as problematic from a validity point of view, as this knowledge may depend on proponent who may lack hindsight into his own limitations and the fact that the findings have not been tested by a third party. On the other hand, all projects are fully documented, and the results have so far been used successfully in industrial practice; some examples of these projects are utilized in the next chapter to exemplify adaptation of the GDA process model to specific contexts.

The first version of the GDA process model was denoted the “overall design analysis process” and is presented in Figure 3 - see(Eriksson and Motte 2013a).

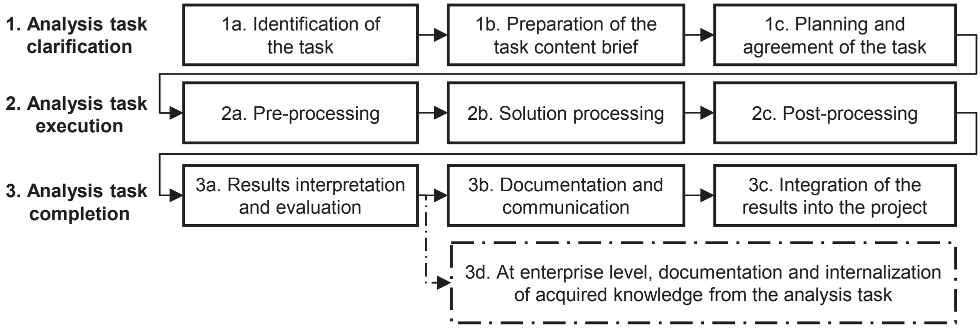


Figure 3. The overall design analysis process model (Eriksson and Motte 2013a).

In a first step towards the establishment of the GDA process model, two modifications of the overall process model are introduced. The first is the removal of one of the activities denoted 3d in the process model. In this activity the knowledge acquired during a design analysis task is included in the enterprise core knowledge system, thus allowing for continuous improvements; though important, this activity need not be carried out after each analysis task. The second modification is a change of terminology. What is referred to here as a phase was denoted activity in the original process model, and activity here replaces the previous term step, in order to create a process model utilizing a terminology which is, in an overall perspective, similar to the one utilized in most engineering design and product development processes.

The modified overall design analysis process model comprises three main phases of a design analysis task: analysis task clarification, analysis task execution and analysis task completion, as well as the activities constituting each of the phases (activity 3d excluded) and original sets of sub activities in each of these activities; not presented in Figure 3 but accounted for in (Eriksson and Motte 2013a). Below brief descriptions of the contents in each of the constitutive activities of the phases are presented. The overall design analysis process model comprises three main phases of a design analysis task: analysis task clarification, analysis task execution and analysis task completion. Below, brief descriptions of the constitutive activities in each of the phases will be presented.

The analysis task clarification phase comprises three activities: identification of the task (activity 1a) in which the objective is to ascertain the task relevance and the actual need for the design analysis activity; the next activity is the preparation of the task content brief (activity 1b); and in the last activity (1c), the objective is on the planning and agreement of the task with the goal to achieve a mutual understanding and agreement on the task ahead and the expected outcome.

In the next phase, the analysis task execution phase, the following activities are performed: the analysis task is processed in the pre-processing step (activity 2a), resulting in a representative engineering model (such as a geometrical model or a functional model) that forms the basis for establishing the computational design analysis model ready to be solved. In the next activity, solution processing (activity 2b), the analysis task is solved (executed) to generate the adequate number of results needed for producing the required results. In the last activity, the post-processing activity (activity 2c), all of the results are post-processed into a form adapted to their future use.

The third phase of the process is the analysis task completion, in which the first activity is the results interpretation (activity 3a), which relates to the interpretation and evaluation by the analyst of all relevant data and information that can be drawn from the analysis task execution. The outputs from the analysis are documented and communicated back into the overall engineering design/development project. This is done in the documentation and communication activity (activity 3b). In the final activity, integration of the results into the project (activity 3c), the utilization of the design analysis project findings is implemented into the engineering design task from which it originates.

In parallel to the development of the process model, a research project was carried out aiming at identifying factors that are exogenous to the design analysis process as such, but that have an important effect on it. In (Eriksson and Motte 2013b) the project and the results obtained are presented in some detail. Also for this project, the findings from the survey in industry (Eriksson et al. 2014) together with the results obtained from the literature survey (Motte et al. 2014) were the main sources of information. Factors are grouped along their levels of influence on the design analysis task; some appear at the basic level of the design analysis and are referred to as endogenous factors, while others appear within the development project, or at the enterprise level, and some outside the sphere of the enterprise, and these are referred to as exogenous factors. The factors elicited in Figure 4 are those that have been deemed to have the most influence on the design analysis process.

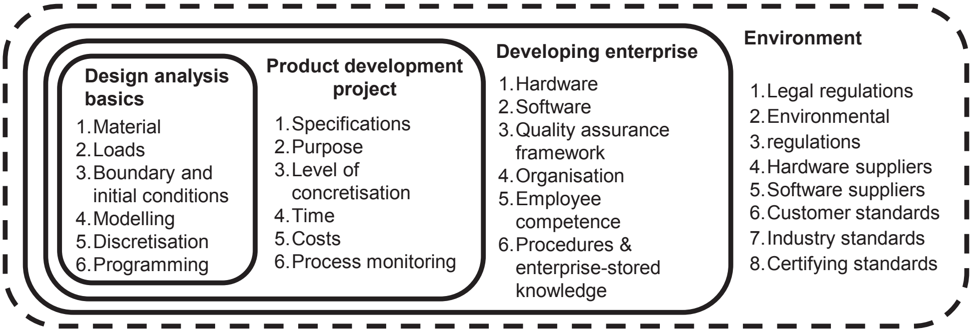


Figure 4. Factors influencing the design analysis process (Eriksson and Motte 2013a).

4.1 The GDA process model

The applicability of the design analysis process model is to be independent of the engineering design process model, design methods, design techniques and design tools utilized during the development of the design solution to be analyzed. In order to achieve this adaptability of the design analysis process model, the constitutive elements of the analysis process, its phases and their corresponding activities must be of a generic nature. Generic, in the given context, alludes to the adaptability of the process model to fit all analysis tasks derived at all levels of concretization of the product-to-be throughout the entire engineering design process and thus also to the overall development processes.

It is important to recognize that the design analysis process model primarily provides a sequence of activities to be followed in order to carry out an analysis task in terms of “what to do” and in “which order”, but offers very little if any support on “how to do it”. In order to be able to answer the question “how to do it”, the first step to be taken is to provide a number of core sub activities for each of the constitutive activities of each of the phases, which articulates the contents of each of the activities. However, this is not enough, as a detailed insight into all aspects associated with the execution of a specific analysis task is required for the selection of a set of methods, techniques and tools, on an operational level, necessary to successfully achieve the goal(s) established for the actual analysis task. Such an insight is only achievable by also considering the influence of the endogenous as well as the exogenous factors, previously described. Utilizing these factors, unique to a specific industrial enterprise, its environment and the actual design analysis task, provides a detailed and adapted approach to the design analysis task or project at hand.

In industry, the information for a design task is most frequently supplied to the analyst by the engineering designer. Since most engineering designers lack profound insight into the engineering design analysis process, the information transferred to the analyst might be fragmentary and in some cases directly misleading. However, even if the information on an actual design task is correct and complete, the analyst needs an overall understanding of the nature of the underlying engineering design problem in order to be able to handle those aspects of the design analysis task that require a more holistic perspective. Examples of these are when an analyst is expected to deliver a proposal for establishment of a strategy for the handling of a complex design analysis task, and when recommendations for a redesign or rejection of an analyzed design solution is expected by the analyst. The need for integration is, in other words, most emphasized in the beginning of the design analysis process and when the analysis results and recommendations, based on these results, are to be communicated back to the engineering designer – this observation was confirmed in the industry survey (Eriksson et al. 2014). However, this does not exclude the need for a more or less continuous exchange of data and information between engineering designers and analysts during all of the activities of the design analysis process. An important part of the integration issue is facilitated by promoting increased exchange of data and information between analysts and engineering designers on a personal level, including direct support by each of the categories when needed; this observation was confirmed during a survey in industry by Petersson, Motte and Bjärnemo (2015).

Exceptions from the described order regarding the division of responsibilities for design tasks and for design analysis tasks are today practiced in some industrial companies. In these, analysts may take over the role and responsibilities of the engineering designers, e.g. by designing and analyzing more or less complex design solutions as a part of an overall design. It is also not uncommon that engineering designers take over the role and responsibilities as analysts of frequently and specially adapted design analysis tasks. In a recently reported survey in international industry, 35% out of 77 companies in 71 countries claimed that engineering designers perform design analysis (predominantly linear static analyses) on a regular basis, and 28% of the companies are planning to introduce engineering designers into the analysis activities in the future (Petersson et al. 2015). These trends are the results of striving for increased efficiency in industry by reducing lead-times and costs, without jeopardizing the quality of the results obtained. This clearly emphasizes the objectives of a generic design analysis process model – to support both analysts and engineering designers in performing design analysis tasks efficiently and effectively by providing an integrative environment on an operational level between engineering design and design analysis.

From additional investigations comprising studies of analysis projects, analysis of the design analysis literature and “best practice” experiences resulted in the need to also modify the original set of sub activities as presented in (Eriksson and Motte 2013a). These efforts resulted in the identification of core sets of sub activities for each of the activities, and also in the awareness that these are not always enough to cover all aspects in every foreseeable design analysis task, thus resulting in the need for adding additional sub activities when needed. After also having introduced these modifications into the original overall design process model, the transition from this into the GDA process model is completed. The first version of the GDA process model is illustrated in Figure 5.

As the adaptation of the GDA process model to a specific design analysis task in industrial practice also requires the “support” given by the factors previously described, the factor model is also included in Figure 5. Note that in the factor model, factors denoted A are of an endogenous nature, while the reminder of the factors are of an exogenous nature.

In order to facilitate the integration between the GDA process model and the engineering design process an approach based on workflow analysis is introduced in the next section.

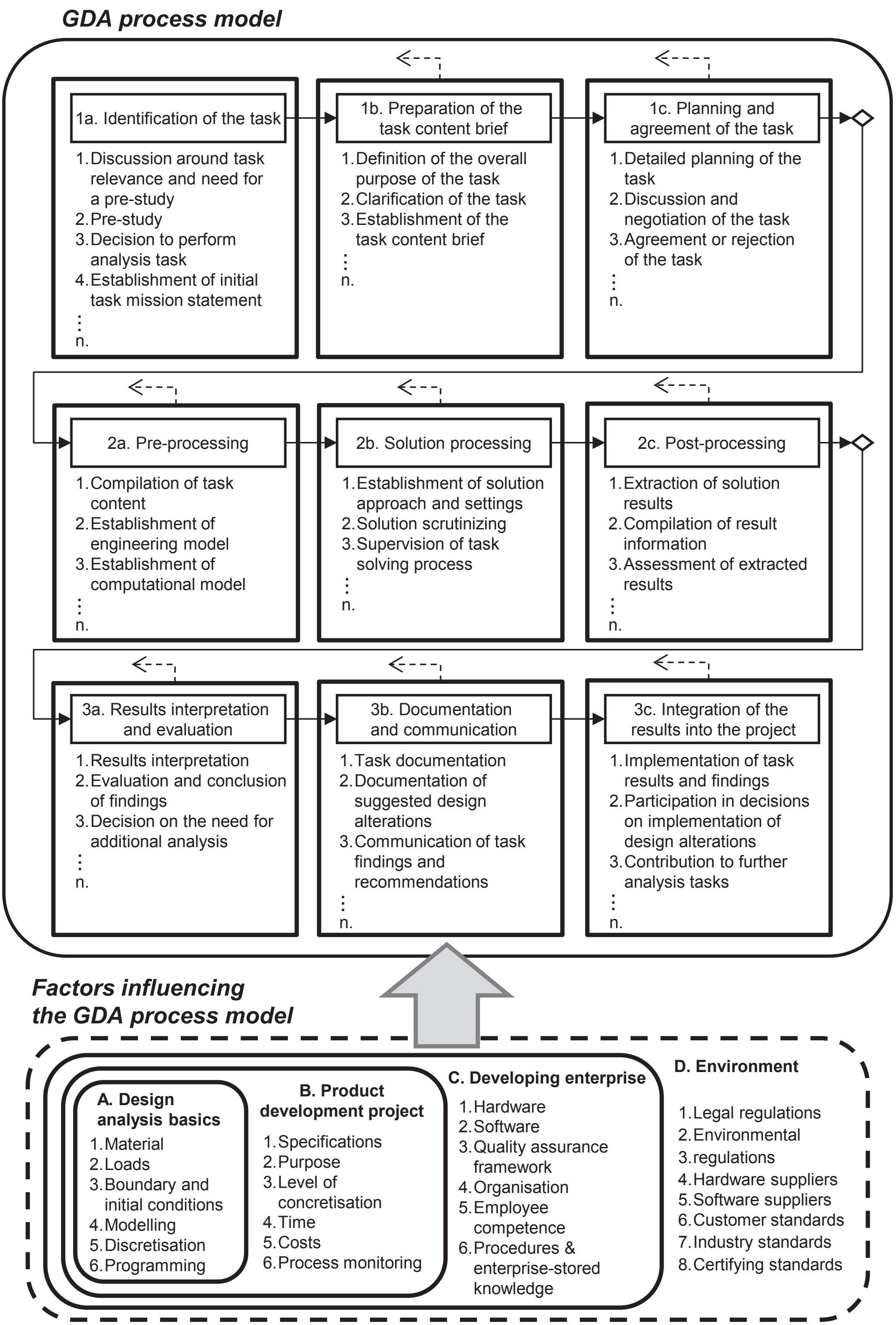


Figure 5. The GDA process model and factors influencing it.

4.2 Analyzing the integrated workflow

Since it is assumed that the engineering design process, its phases, activities and sub activities are not known in advance, the first activity to be carried out in order to be able to describe the design analysis workflow in some detail is to fully describe the constitutive activities of the ED activities and/or the ED process on an operational level. If a similar notation of the activities as presented in Figure 5 for the GDA process model is also introduced for the ED process activities, it is possible to fully describe the workflow between interacting activities throughout the entire design analysis project. The introduction of arrows between interacting activities provides information on the direction of the workflow and facilitates an easy way of illustrating the workflow. The possibility to extend the notation to include all processes involved in a design and development project might extend the possibilities to illustrate and describe the workflow to comprise the entire workflow during a PI project.

Implementing additional information associated with the different notations, such as time elapsed, costs, type of software utilized etc., in a database system makes it possible to gain a deeper insight into and supervision of a specific part or entire workflow during a design analysis task or project. This information might be utilized to study bottlenecks in the workflow as well as unexpected events and other circumstances of interest and thus of major importance for a future improvement of the design analysis process. The possibility to compare workflows between different analysis tasks and projects facilitates comparisons between design analyses, as well as the possibility to identify specific workflow patterns that repeat themselves in frequently occurring analysis contexts or situations, thus enabling adaptations of the GDA process model to fit these circumstances.

5 Exemplification of the use of the GDA process model to frequent design analysis tasks in industrial practice

During the interviews in the industry survey (Eriksson et al. 2014), it was found that a significant number of design analysis tasks were referred to in terms of contexts originating from engineering design and/or design analysis problems of a common nature. A total of four such contexts were identified during the interviews. It should be noted that these contexts represent a significant part of all analysis tasks originating in industrial practice. A rough estimate made by the authors, based on the findings obtained during the interviews, on their own experience as well as on design analyses referred to in the literature (Eriksson et al. 2014; Motte et al. 2014), indicates that these represent 65 – 75 % of all design analysis tasks. The identified contexts are:

(1) Explorative analysis
(2) Evaluation
(3) Physical testing
(4) Method development

Since the intention underlying the development of the GDA process model is to provide a generally applicable and adaptable design analysis process model that fosters integration of design analysis in engineering design on an operational level, the GDA process model is expected to efficiently and effectively handle all types of design analysis tasks, and thus also those emanating from the contexts presented above. In order to demonstrate the potentials provided by the GDA process model, one example from each of these contexts is to be presented below. The choice of analysis tasks from each of these contexts to some extent "randomizes" our selection process while simultaneously covering essential contexts or categories of analysis tasks in industrial practice.

Whenever projects emanating from industrial practice are to be presented, issues of a sensitive nature like business secrets, business plans, expert knowledge and proprietary information have to be considered. This reduces the possibility to give a complete account of all aspects of such projects. In the examples to be presented below, restrictions of this nature constrain our presentations in a number of ways, but especially regarding our possibilities to reveal detailed information. This limits our possibilities to demonstrate the influence of the factors influencing the actual design analysis project to an extent that makes it impossible to present their use. The presentations are thus confined to a demonstration of the power of the GDA process to fully describe the workflow in a design analysis project that might be used in the future as a platform for developing an adapted workflow model for the specific context, thus enabling planning and control of future projects of the same nature and origin. For the illustration of the actual workflow in each of the examples, the notation introduced in section 4.2 is utilized. In order to elaborate on the nature of the design analysis tasks and their relation to the engineering design process in general terms, an introductory text on each of the contexts precedes the subsequent presentation of the design analysis project/task.

5.1 Explorative analysis

It might be argued that in a broad perspective most design analysis tasks are of an explorative nature, since this implies that the design analysis activities are aiming at the determination of important design parameters associated with an existing or predefined design solution, thus providing the necessary results and insights to be utilized by the analyst and/or engineering designer to fulfil a specific purpose initially established for the actual design analysis task. In this perspective a straightforward design analysis task is of minor interest when intending to demonstrate the potentials provided by the GDA process model.

One of the single most important activities within the engineering design process is the creation of technical solutions - ranging from simple details to complex product systems and new working principles on which the product-to-be might be developed as described in (Pahl et al. 2007; Ulrich and Eppinger 2012). In the engineering design literature these activities are usually referred to as design synthesis or just synthesis for short. Traditionally, these activities are handled either by an engineering designer or by a design/development team, utilizing intuitive as well as discursive methods (Pahl et al. 2007). Resulting from the introduction of design analysis methods and tools, especially FE-based, it has become possible for the engineering designer to utilize design analysis of the proposed design solution candidates to analyze different solution paths more thoroughly than ever before and thus be able to more or less fully explore the design solution space at hand. These analyses are traditionally performed by an analyst, who is either an in-house or an external consultant. In some cases the engineering designer might take over the role as analyst on his/her own, when predominantly confined to linear analyses (Petersson et al. 2015). However, it is not uncommon that analysts make suggestions for modifications or redesigns and in some cases also propose completely new design solutions. Finally, it is important to note that the synthesis tasks to be performed throughout an engineering design project are numerous, and not all of them lend themselves to design analysis in the given context due to impracticability and other difficulties associated with the actual synthesis tasks.

The explorative approach to synthesis has significantly contributed to deeper insights into the potentials provided by different design solution candidates and thus to more technically advanced solutions (Petersson, Motte, and Bjärnemo 2015). Adding statistical and stochastic as well as optimization methods and tools to this approach makes it also possible, at least theoretically, to fully explore the entire design space by determining the ultimate potential for each and every one of the design solution candidates; thus not only producing the optimal solution candidates but also providing the essential facts needed for an analysis of the robustness of the design solutions. In much of the current analysis software it is not only possible to more or less automate the entire approach, but also to generate the actual solution candidate by utilizing different statistical design exploration methods such as composite difference algorithm, space filling methods, DOE methods and response surface methods (RSM) and goal driven multi-objective optimization methods such as shape optimization, and topology optimization (Eriksson 2003; 2014). A somewhat different, but closely related, approach to design synthesis as presented here is generative design, in which evolutionary algorithms are utilized in design synthesis – see Nordin (2015).

For demonstrating the use of the GDA process model in explorative analysis, a synthesis-oriented explorative analysis task has been chosen.

5.1.1 Exemplification of a synthesis-oriented explorative analysis task – the design of a bumper

In designing a bumper beam system, as part of the overall crash management system, an important task is to assure accurate predictions of the consequence of various crash scenarios given different objectives. For low speed impacts, up to around 15 km/h, the focus is on evaluating repair cost of the damaged bumper system and for intermediate speeds between 15 and 40 km/h the main focus is pedestrian safety. For crash scenarios at higher speeds, above 40 km/h, the focus shifts to driver and passenger protection. A number of standards and legislations in Europe (ECE R-42, AZT, Euro NCAP) are available that outline various scenarios to which the system should comply.

In this example a centre pole impact of the mono rear bumper beam is introduced in Figure 6 as an exemplification a design analysis task of a synthesis-oriented explorative nature, including an investigation on parameter settings. The purpose of the analysis scenario is to study the intrusion during a low speed impact in order to reduce the insurance cost which is directly related to the predicted level of damage occurring during the impact scenario. Higher intrusion indicates increased risk of damaging costly parts in the rear end of the car resulting in higher insurance costs.

The initial information from engineering design to the design analysis activities (1) is a short description of the problem at hand, and since the request came at such an early stage of the design work, the design space is quite open for alternative design solutions. During the following discussions (2) it was found that a synthesis-oriented explorative design analysis task would be the preferred approach to solve the design problem at hand. The discussion were summarized and documented in a preliminary mission statement. Note that Validus Engineering AB is a Swedish consulting enterprise, hence the request.

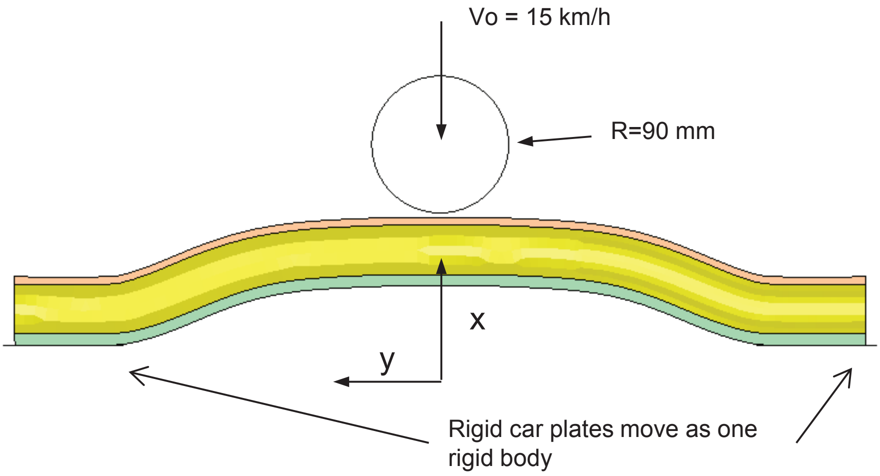
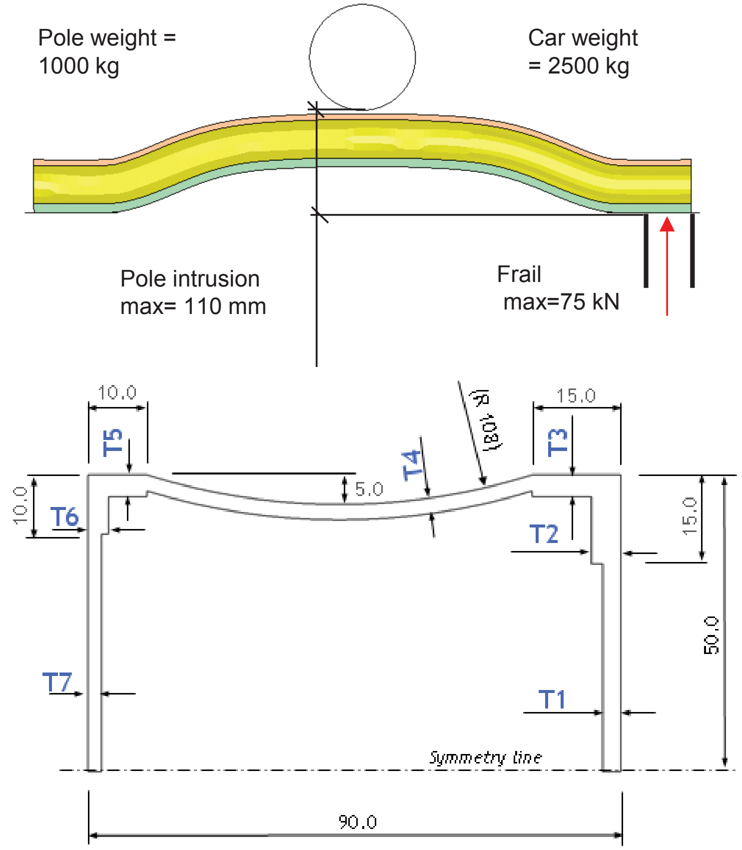


Figure 6. Impact model to pole (courtesy Validus Engineering AB).

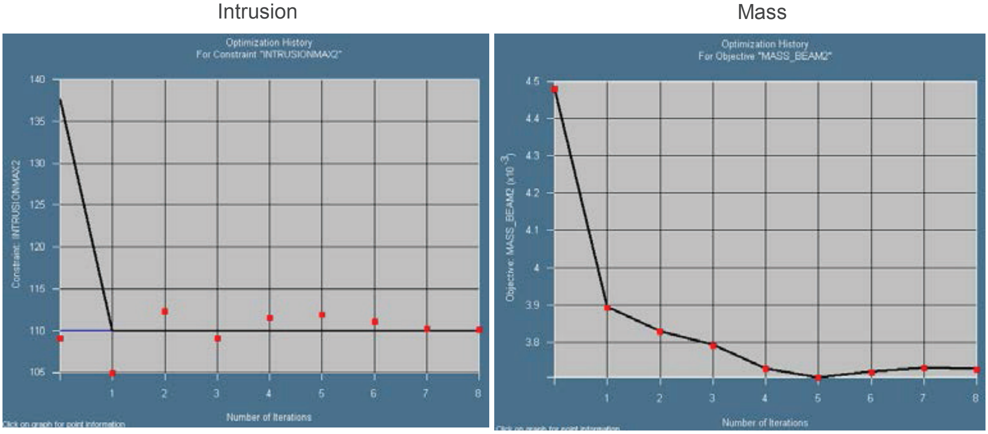
During the next activity, to further clarify the task, discussions within the project team regarding general conditions of the analysis scenario (3) took place. The analysis scenario consists of a 15 km/h central impact against a rigid pole of radius 90 mm as displayed in Figure 6. The type of result to be extracted was agreed upon as well as the various input data of the pole and how the interface between the bumper system and the remainder of the car should be established - see Figure 7. Furthermore, decisions were also taken regarding the constraints and the output quantities, such as the objective of mass and the constraints as shown in the top picture of Figure 7. The objective for the design analysis task was to minimize the weight while complying with constraints on intrusion and force into the car crash rail. Also the project time made a constraint that demanded a specific analysis method to be used in order to keep execution time and related costs as low as possible. The information known at this point in time was put into the task content brief for final acceptance of the task.



Bumper cross section

Figure 7. Top: constraints setup. Bottom: model parameters (courtesy Validus Engineering AB).

However, due to the time span between the preparation of the task content brief and when it was actually decided to initiate the execution of the analysis project, there had been some development on other production related engineering design activities (4) constraining the design freedom on thickness parameters, as shown in the bottom part of Figure 7, to some interval values. This was reflected in an updated version of the task content brief (5) before the final planning and agreement on the task could be finalized (6). The computational FEA model shown in Figure 7 was established with shell elements that were found adequate for evaluating the response. The car and the pole were both represented as rigid parts, implying that they are only allowed to translate in the x-direction, meaning that energy during the impact should be absorbed by the bumper and transmitted into the car plates. The model setup was communicated to the project team (7) to assure that no new information was available before the solution processing was initiated. The solution process set out for this task was to use a d-optimal based design space investigation with 13 points based on full factorial design of experiment (DOE) with 5 levels to establish the base configuration for a linear metamodel-based response surface model optimization (RSM). Maximum number of iterations was set to 8 and tolerance on acceptable results was set to less than 1 % change in both mass and thickness compared to previous iteration optimum. Thus the total number of analyses to be performed is 8*13+1= 105 and the results show that two feasible designs, 1 and 3, exist for the intrusion constraint - left picture in Figure 8. Iterations 7 and 8 are close to feasible.


Intrusion

Mass

Figure 8. Left: intrusion as a function of iteration. Right: mass as a function of iteration (courtesy Validus Engineering AB).

The results were post processed and the accuracy predictions in the metamodel were investigated by performing an additional analysis of iteration 3 that showed that the predicted value corresponded to the calculated value. The results were then further assessed and the findings were communicated back (8) to the project team with the purpose of challenging the constraint level set on intrusion since it could be shown that the parameter configurations of iterations 7 or 8 resulted in lower masses than the feasible iteration does. However, this was not found practicable and therefore the current set of results should be further evaluated and documented. The main results were thus collected in a documentation describing the task performed, and the following main findings were reached:

- The analysis results in a feasible design at iteration 3 with mass of 3.79 kg. This is established through 3 successive generations of linear RSM:s and 40 FEA.
- Additional reduction in mass (about 1.6%) to 3.73 kg is found in the “nearly” feasible designs in iterations 7 and 8 with 110.2 mm and 110.1 mm intrusion respectively (110 was the criterion); see right picture in Figure 8.

These findings were then communicated and presented to the project stakeholder (9) with the message that there is a possible gain in mass reduction if some adjustment could be allowed on the intrusion constraint against a rigid pole of radius 90 mm as displayed in Figure 6. The outline of the workflow during the bumper design analysis task is shown in Figure 9.

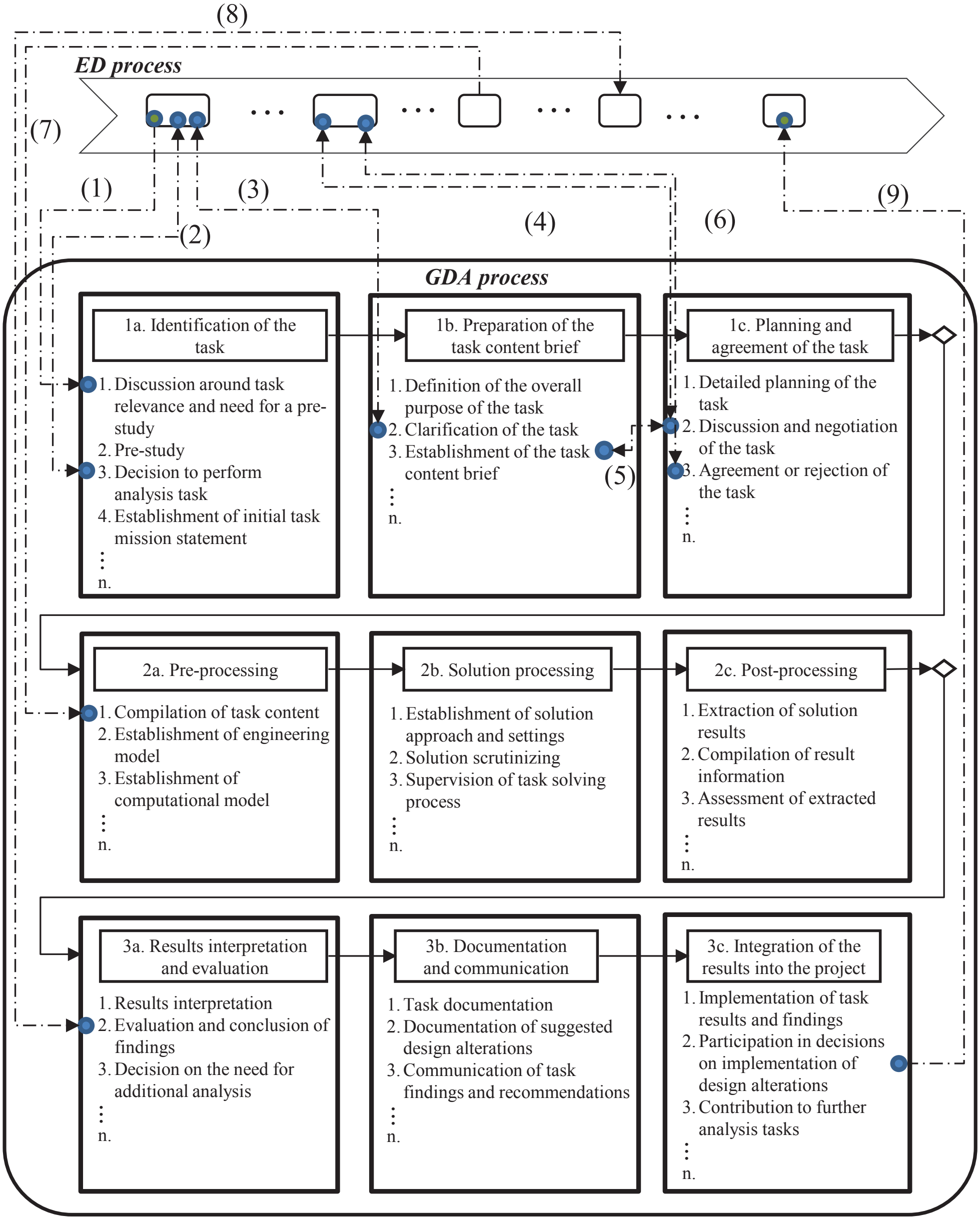


Figure 9. The workflow during the bumper design analysis task.

5.2 *Evaluation analysis*

During the engineering design process, hundreds or sometimes even thousands of tasks are carried out in order to attain the final result in the form of a new or improved component, sub system or product. In a significant number of these tasks, decisions are made as to accept, modify or reject the design solution under investigation. The nature of these decisions might range from limited decisions on a single attribute to complex multicriteria decisions in which the decision maker is facing a decision problem involving several, often contradictory, aspects of the solution candidate that have to be taken into account (Vincke 1992).

In industrial practice design criteria geminate from product specifications. A specification (singular) is a formalized account of the expected feature(s) a given solution candidate has to possess in order to fulfil the identified need from which the specification originates. In the "simpler" cases the engineering designer usually makes the decision on his/her own, while in the more complex cases decisions are made by teams, usually by cross-functional teams. The common denominator in all decisions is the access to knowledge of the "value" or "usefulness" of the solution candidate under examination. This knowledge is provided as a result of an evaluation of the solution candidate with reference to the expected performance expressed in terms of a design criterion. In engineering design practice, a number of approaches are utilized for such evaluations, ranging from subjective estimates based on the engineering designer's experience of similar designs, through testing of prototypes, to the use of design analysis and formal decision matrices.

When utilizing design analysis in design evaluation, the result obtained is usually confined to quantitative information on a specific design parameter(s), which is used for an immediate decision or to be used in a subsequent multicriteria decision activity. Due to costs and time needed for performing a design analysis task, this approach is usually confined to those cases when the design parameter(s) under examination is crucial or directly decisive for the acceptance, rejection or modification of the design solution candidate under examination.

The initial problem when utilizing design analysis in design evaluation is the difficulties of "translating" the often very complex and vague product specifications into fully operative design analysis criteria. The process of translating is mainly carried out in the form of discussions between the engineering designer and the analyst. Exceptions from the described procedure occur when predefined design analysis criteria are supplied by an external source, e.g. from a classification society such as DNVGL, Lloyd's Register and American Bureau of Shipping.

Finally, in the words of Vincke (1992, xv) regarding the important difference between optimization and multcriteria decision-aid: "The first fact which should be noted when dealing with this type (multicriteria, author's comment) of problem is that there does not exist, in general, any decision (solution, action) which is the best simultaneously from all points of view. Therefore, the word 'optimization' doesn't make any sense in such a context; in contrast to the classical techniques of operations research, multicriteria methods do not yield 'objectively best' solutions (such solutions do not exist)."

5.2.1 Exemplification of an evaluation-oriented analysis task - evaluation of vertical acceleration criteria of a DTS frame structure.

This example presents the evaluation of the frame structure of a device transportation system (DTS) (DTS, Eriksson and Burman 2005; Eriksson et al. 2014) developed for a semiconductor device, hereafter referred to as the "shipped device"; see Figure 10. The shipped device is sensitive to high acceleration levels and is to be shipped by different means of transportation, which places demands on the DTS (see Figure 10 for a schematic overview of the DTS that insulates the shipped device from vibrations and shocks during shipment). The main demand on the performance of the DTS is that the acceleration level on the shipped device at any point and at any time should not exceed specified levels. This includes both horizontal and vertical shock loads as well as vibration. The vertical shock demand is selected for exemplification in the current publication.

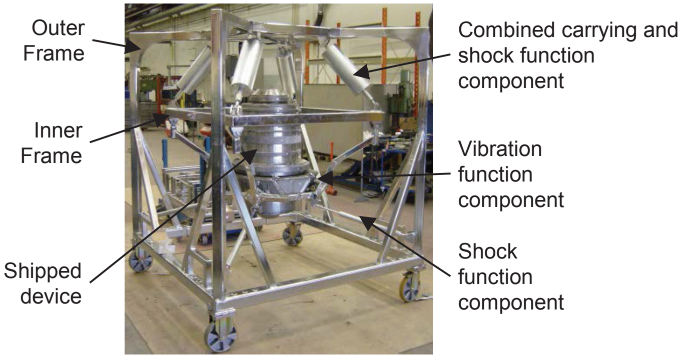


Figure 10. Overall description of the shipped device as well as the DTS (courtesy Validus Engineering AB).

The mentioned requirements together with the additional logistic and product-specific requirements were included in a product specification, and the DTS development project was initiated. During the task clarification of the initial design analysis task of the system, the appropriate combination of design analysis software (MBS and FEA in this particular case), and resources were discussed (1). The different limitations as well as potentials in the combinations were assessed in order to judge the effect of uncertainties on them in relation to the design analysis task ahead based on the present state of knowledge both within the project and also within the enterprise.

A pre-study of various working principles with an established MBS computational model as shown in the left picture in Figure 11 was performed in order to assess the demand on acceptable acceleration levels. The outcome of this pre-study was communicated to the project team (2) and the decision was taken to initiate a design analysis task of the frame structure (3). Furthermore, the choice of a representative selection of load cases, out of all defined load cases in the specification, required for fully developing the design was decided upon and included in the task content brief (4).

The initial FEA computational model was established as shown in the middle picture in Figure 11. The frame was given only principle beam properties and geometrical layout in order to represent the needed volume of the solution with regards to the movement required as described by the MBS analyses results. The principle frame data were established and refined during an iterative design analysis process in which the MBS forces were transferred into the FEA where the structural response was studied. The objective of the analyses was to find some overall geometrical beam data that would be feasible from a material yield strength perspective.

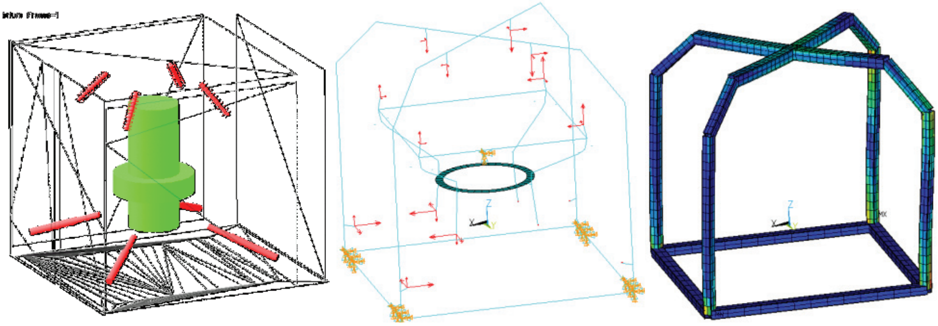
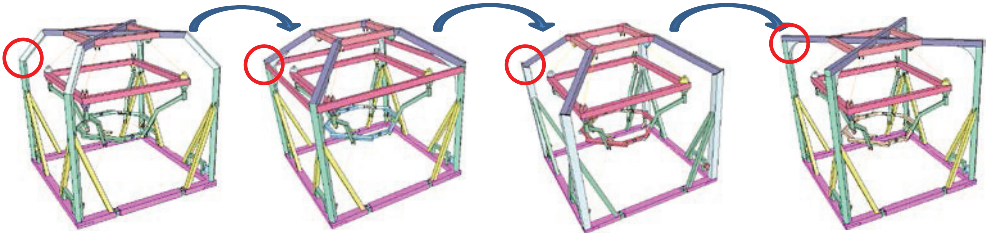


Figure 11. Presentation of the initial MBS and FEA models as well as the FEA results (courtesy Validus Engineering AB).

The results, as shown in the right picture in Figure 11, as well as component data were communicated to the project team and the component suppliers through review meetings (5). During the review the supplier provided updated information regarding the shock function component for which the damping coefficients shifted from the linear to non-linear characteristics. This information was included in an updated task content brief (6) that was discussed and agreed upon (7). During the following activities the basic layout of the frame structure of the DTS was further developed and evaluated in close collaboration with the engineering design department, in which the updated task content brief formed the basis for the FEA analysis (8). Figure 12 presents a number of the frame layouts evaluated in the iterative progression of design analysis (9) and engineering design (10) with the defined purpose of finding a suitable overall layout with the initial model on the left and final model on the right. Preliminary layouts for the auxiliary functions of handling the DTS during transport were also included in order to incorporate them into the complete system.



Layout 1 Layout 2 Layout 3 Layout 4

Figure 12. Preliminary layouts for the DTS (courtesy Validus Engineering AB).

In Figure 13 the results from the vertical shock load are presented for the four preliminary layouts. Accelerations (Acc.) are presented as a function of time vs. acceptable (requirement) acceleration and Equivalent von Mises stress is presented as a function of time vs. acceptable (requirement) stresses. All preliminary layouts comply with the acceleration specification, but when also studying the stress levels in the upper corner of the vertical beams in the outer frame (see red circles in Figure 12) it can be seen that the fourth layout has the overall lowest stress levels during collision.

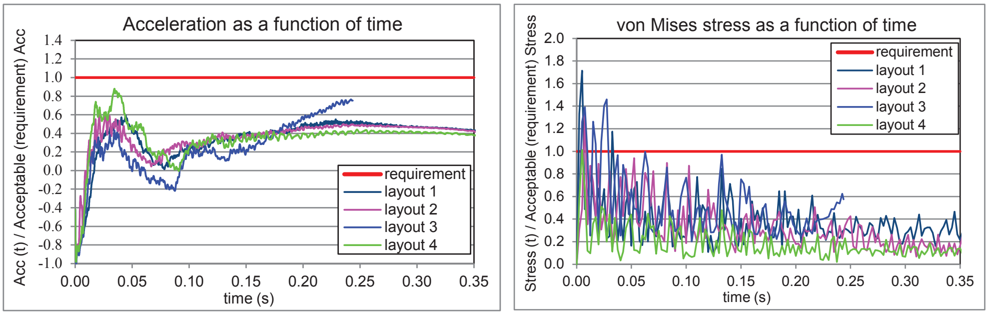


Figure 13. Comparison of results from the different preliminary layouts of the DTS (courtesy Validus Engineering AB).

During the results interpretation it was concluded that the fourth layout also generally performed better than the other layouts when studying the other load cases included in the product specifications. The combination of the global and local stiffness together with a general low stress state in the fourth layout made it the most suitable layout for further development in the following design phases, which was communicated to the project team (11).

The outline of the workflow during the evaluation of the outer frame of the DTS is shown in Figure 14 with numbers within parenthesis.

5.3 Physical testing

Since all design analysis results are derived from analysis models, the validation of these models through physical testing constitutes a key activity in most design analysis projects and tasks. Validation in the given context is here defined as: “The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.” (AIAA 1998, 3)

In the planning for a physical testing project, application of measurement systems such as strain gauges and load cells might call for additional design analysis activities to establish position and other measurement parameters related to the actual testing activity.

Even during the most carefully planned physical test campaign, unexpected events may occur. In order to investigate the root cause of such events, design analysis is a powerful tool. A closely related objective is the investigation of root causes of events occurring during use processes based on identified damages, failures or other specific related causes. Design analysis is also a powerful means to perform post-test sensitivity and discrepancy studies in order to elaborate on deviations found when comparing data from physical tests and design analysis results.

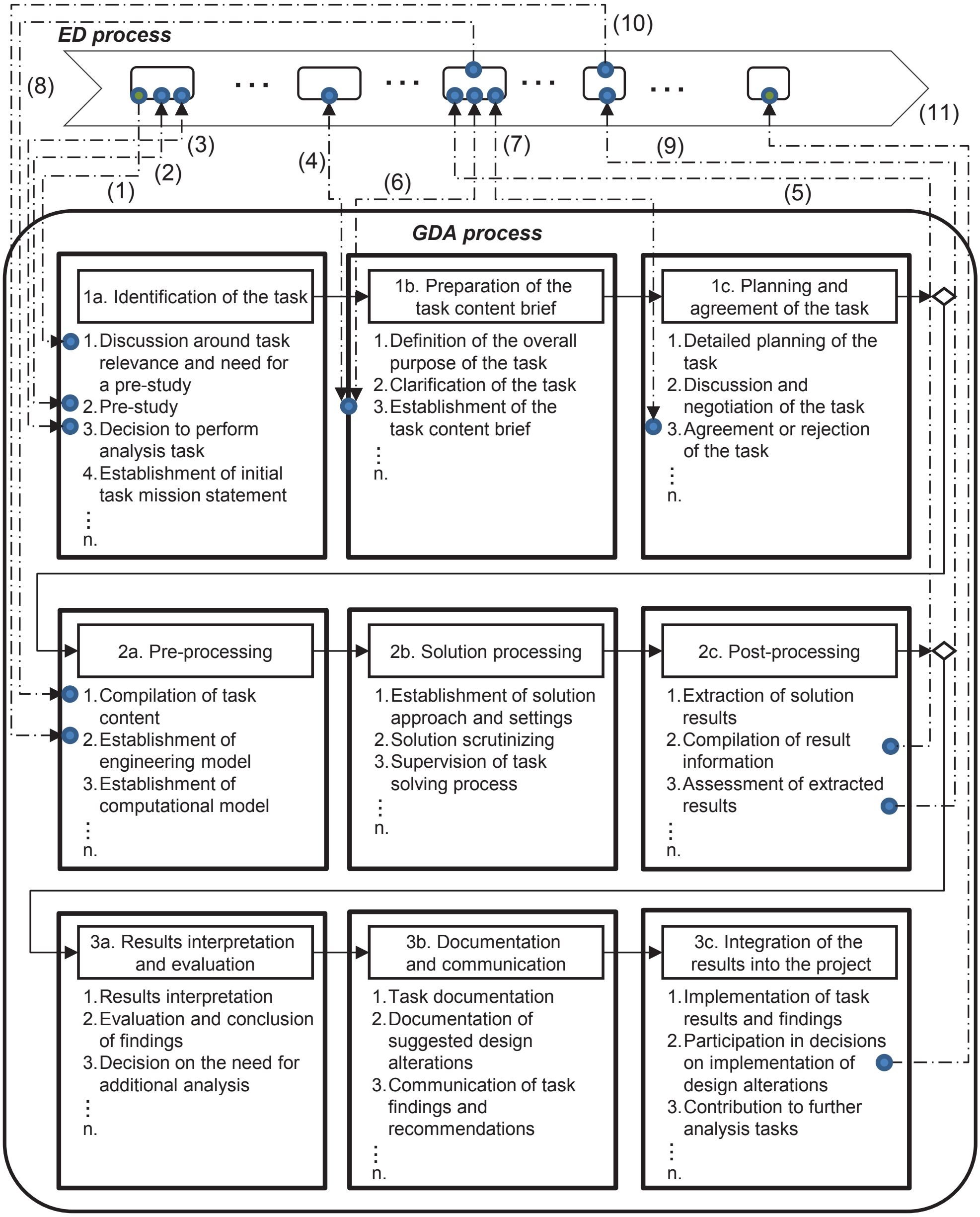


Figure 14. Workflow during the evaluation of the outer frame of the DTS.

5.3.1 *Exemplification of a physical testing – acceptance testing of design transportation system*

This example presents one of the final physical acceptance tests of the DTS that was discussed in Section 5.2. In total three different types of tests was performed, and in this example the drop test is selected for discussion:

(1) Collision test
(2) Drop test
(3) Vibration test

In this example the drop test has been selected for the illustration of the workflow during a physical test. During the task clarification of the design analysis activity (1), the appropriate combination of design analysis software (MBS and FEA in this particular case) to be used in the validation comparison of the physical test data with the obtained design analysis results was selected. The limitations and potentials of the selected software were assessed in order to estimate the effect uncertainties would inflict on the analysis results in relation to the design analysis activity ahead, based on the present state of knowledge of the actual project and also within the enterprise emanating from the preceding design activity. In the current case, approaches based on MBS and FEA were compared and a decision was made to include assessments from both types of software (2).

The purpose of the design analysis task was to support the testing and the specifications established that the drop test should be performed from a drop height of 100 mm to avoid damage to the floor and local damage of the DTS. The drop test is divided into three phases: free fall, impact and retardation. The test scenario and placement of measuring points of the strain gauges, accelerometers as well as displacement and velocity transducers on the structure is shown in Figure 15. The initial proposal on the number and placement of measuring devices is based on a study of available design analyses results and documentation from the design work (3). The task content brief was established and the task was agreed upon.

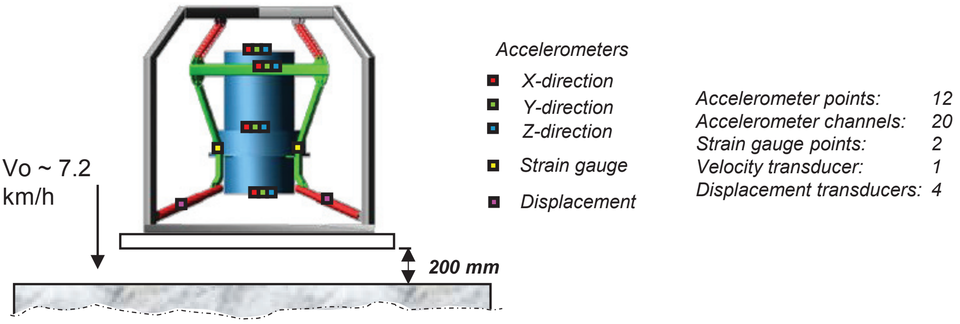


Figure 15. Drop Test description and placement of measurement system (Accelerometers, Strain gauges and displacement) (courtesy Validus Engineering AB).

The pallet, see left picture in Figure 16, supporting the DTS during the testing was designed (4) and analysed as a pre-test analysis in order to asses that it will be able to sustain the loads during the various test scenarios. The representations of the shipped device and DTS were also extracted from the development project (5). In the right picture in Figure 16 the state of stresses from the static loading is displayed; this was communicated back to the project for review (6). Note that only the outer frame and pallet are displayed for clarity. The interpretation and conclusion of the various cases studied was that the pallet design proposed was capable of withstanding the loading for all cases. These findings were communicated back to the project for further design and manufacturing of the pallet and preparing for physical testing (7), as well as for initiating actual design analyses of the validation scenario using both ADAMS and LS-Dyna (8).

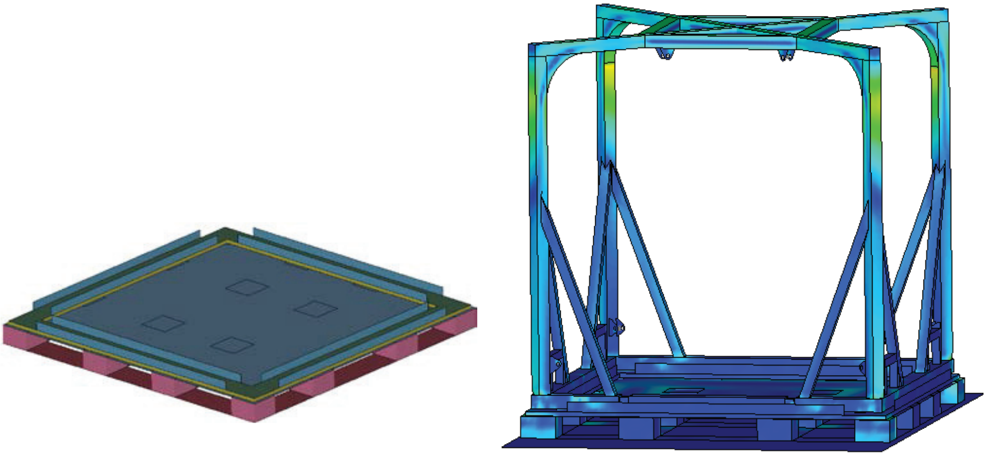


Figure 16. Pallet design and stress state from static loading scenario (courtesy Validus Engineering AB).

Based on the post-processing of the analysis results from the LS-Dyna analysis further information regarding the originally proposed measuring points was reviewed and some small changes were proposed (9). Incorporating them resulted in the actual test-setup as shown in Figure 17 with the DTS mounted on the pallet prepared for a drop into a 1-meter-thick concrete floor from 100 mm. In the right picture in Figure 17 the resulting accelerometer positions are shown.

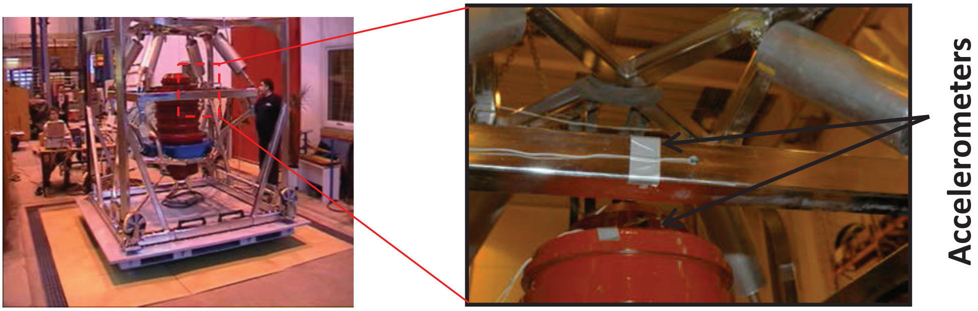


Figure 17. Drop test set up for the DTS (left) and positioning of the accelerometers (right) (courtesy Validus Engineering AB)

The execution of the actual physical test scenario gave the results presented as red curves in Figure 18. Dimensionless quantities are used in the graphs, and ±1 represents the criterion on the DTS. The measurement point is at the top of the shipped device. These results were communicated to the analyst (10) and used in the comparison between the test data and the extracted analysis results from the ADAMS analysis as shown in the upper picture in Figure 18, which shows quite good agreement in the free fall and retardation part of the event. However, the peak at impact is not captured accurately enough to judge validity. The comparison between the test data and the LS-Dyna analyses results shows a good correlation for the peak values.

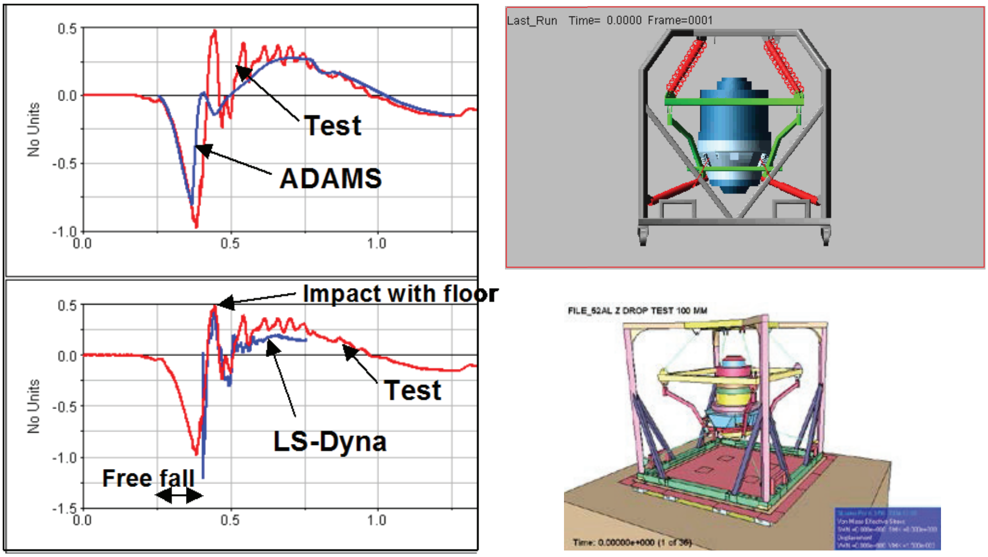


Figure 18. Upper picture: ADAMS model and results comparison with test data, Lower picture: LS-Dyna results comparison with test data (courtesy Validus Engineering AB).

The conclusion drawn from the validation comparison is that neither analysis approach is capable of capturing the whole event nor alone able to provide the necessary facts needed for the acceptance of the criterion. Instead both the ADAMS and LS-Dyna analyses are capturing different aspects of the event to adequately describe the complete drop test scenario. The ADAMS analysis is used to predict the overall information from the event and LS-DYNA is used to predict the acceleration levels at and after impact with the floor. This conclusion is documented and communicated to the project team through a final product acceptance meeting where the analysts as well as the engineering designers involved in the testing were present to elaborate on the inferences from the validation comparisons (11). The outline of the workflow during the physical testing of the DTS is shown in Figure 19.

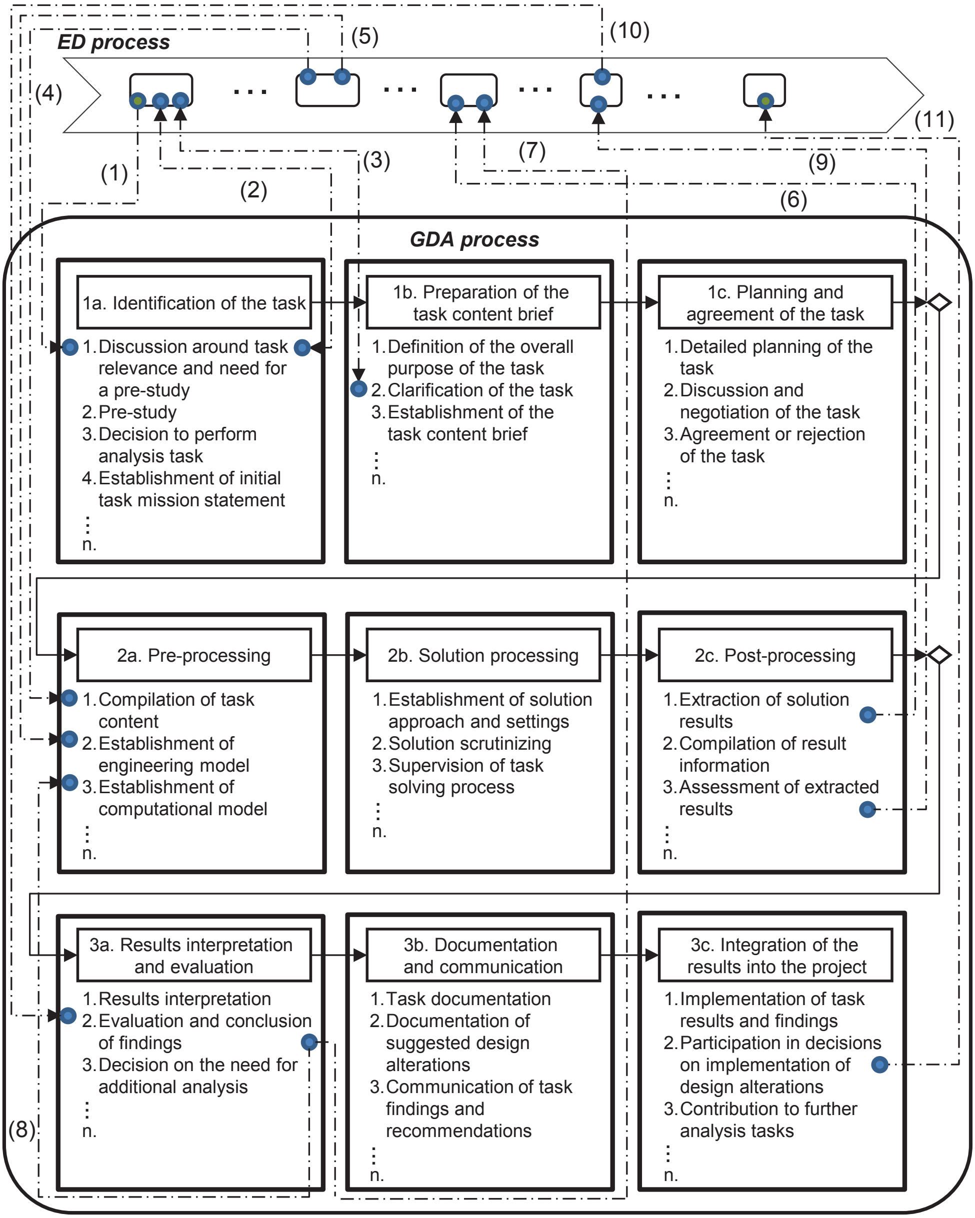


Figure 19. Workflow during the physical testing of the DTS.

5.4 *Method development*

Method development is the unifying context for two fundamentally different "sub contexts”. The first of these sub contexts arises, as previously described, when an enterprise is striving for increased efficiency in design and development projects in which design analysis plays a major role. The increase in efficiency is achieved by allowing engineering designers to undertake parts of, or the entire, design analysis activity traditionally performed by analysts. The initially expected outcome of this approach was decreased costs and lead times without jeopardizing the quality of the results obtained during the design analysis project. Later experience shows that the benefits of costs and lead-times instead are used to obtain deeper knowledge of the product technology, and to improve the designer's knowledge within design analysis, which in turn resulted in increased collaboration with the analysts (Petersson, Motte, and Bjärnemo 2015).

Since the majority of engineering designers lack the experience and skills of an analyst, the design analysis tasks to be undertaken must be adapted to fit these constraints. The most frequent approach to accommodate this adaptation is to initially identify frequent design analysis tasks for which tailor-made guidelines or procedures can be developed and expressed in terms of step-by-step activities to be followed by the engineering designer. These guidelines and procedures are usually referred to simply as methods. The development of these methods should include experiences gained and lessons learned from previous design analysis projects. In other words, the methods should be verified and validated before they are approved for use in industrial practice.

Responsibility for development of these methods usually lies with a team of analysts responsible for the engineering design and design analysis activities. These responsibilities also include the necessity of active participation of analysts in the training of the engineering designers as well as supervision of their analysis efforts, at least initially. Since the participation of analysts needs to be kept at a minimum, in order to achieve the expected increase in efficiency, KBE systems are utilized in parallel to the traditional design analysis tools, in order to provide the necessary support throughout the entire design analysis process. The development, verification and validation of the KBE tools are also the responsibility of the method development team.

The nature of the design analysis tasks to be undertaken by engineering designers might range from very simple to complex. It is, in other words, fully possible to allow an engineering designer to undertake design analysis tasks of a complex nature e.g. involving elements of multi-physics analysis, without increasing the risks associated with the actual analysis task (Petersson, Motte, and Bjärnemo 2015).

The second sub context arises when the experience and skills of an analyst are not sufficient to assure minimal risks and complete control of all of the activities constituting a design analysis task. This category usually occurs when the demand for full control of the entire analysis process is a must, often required by some external body such as a classification society, or in the development of military equipment; this may also occur in an enterprise when extraordinary demands on product quality and safety exist.

Responsibility for development of these methods usually lies with the project leader in close cooperation with a team of analysts responsible for the engineering design and the design analysis activities within the enterprise. In some cases representatives for external stakeholders also participate in these activities. The development of these methods should also include experiences gained and lessons learned from previous design analysis projects, including verification and validation before a method is approved for use in industrial practice. An example of such method development is presented in (Mårtensson, Forsman, and Eriksson 2009) , in which a tool for establishing quantitative measure of the risk of later encountering HCF life-limiting vibrations of both rotating and stationary parts was the goal.

An additional category belonging to the second sub-context arises from those cases when a previously unknown analysis task is to be solved, or when a new or improved analysis technique is developed for existing analysis tasks, and the objective might be to improve the performance of the analysis process. For these tasks a technology development activity is performed by a team of analysts sometimes also including engineering designers and the managers for these functions, project leaders and, if applicable, representatives from external bodies. Since the result of such a technology development project is presented in the form of step-by-step activities, the term method is also valid here and used to denote the results of these activities.

5.4.1 Exemplification of method development – development of a template for analysing a valve in a combustion engine

In the automotive industry, new and more extensive environmental demands on emissions from combustion engines force manufacturers to optimize performance of their engines. One component in such an engine that is especially affected by these efforts is the exhaust valve and its seating. The traditional procedure in the design of an exhaust valve – seating arrangement is that the engineering designer generates a design solution that is handed over to the design analysis department for evaluation. As the analysis department usually has very limited time for such design evaluations, predominantly due to high capacity utilization, this results in this type of analyses are given low priority such that the lead times for a project of this kind are not acceptable to the engineering designers.

It was therefore decided that the engineering designer in charge of the design and development of the exhaust valve and its seating should carry out the generation and evaluation of the concepts on his/her own. As the engineering designer usually lacks deep insight into design analysis, it was expected that performing design analysis on his/her own should introduce major problems that would demand extensive support (Petersson et al. 2015). To be able to handle these problems and thus allow the engineering designer to generate and evaluate an extensive number of different exhaust valve–seating concepts on his/her own, it was decided that template based design analysis (TBDA) should be introduced. TBDA is defined in (Petersson, Motte, and Bjärnemo 2015) as a pre-developed code that supports or guides the person performing design analysis tasks, e.g. from predefined settings available in traditional CAE tools to scripts developed in-house and advanced usage of knowledge-based systems (KBS).

In the example presented here, a template is developed for the design analysis of the exhaust vale-seating design, utilizing method development. Developing such a template generates high development costs, but as such a template can be used for a number of different sizes of combustion engines, the cost for the development could be accepted. When the enterprise chooses to start a method development for a specific type of task, there is, in most cases, a dedicated person or group at the enterprise level that is responsible for the method development of the template and implementation/training provided to their engineering designers. This group also discusses with the design analysis department and/or the person responsible for that department in what project or for which product the template is to be used (Petersson, Motte, and Bjärnemo 2015).

During the project planning, discussion around task relevance and a need for a pre-study (1) was agreed upon. A pre-study (2) was performed. After evaluating the results from the pre-study and establishment of a preliminary mission statement (3), it was decided to perform a method development (4) for this type of design task (conceptual exhaust valve-seating designs). Since the method development should result in a template to be used by an engineering designer who does not have adequate knowledge of design analysis, there were many different types of issues to be resolved.

One important issue is the quality aspect of the template and how to ensure that the users can only do things that they are allowed to do. It was decided during the definition of the overall purpose of the task (5) that the implementation of KBS into the developed template should provide the quality assurance. It was also essential to make the implementation of the template user friendly by developing a special user interface with the help of Visual Basic programming – see left picture in Figure 20. The user interface and the possibility to read and write from a spread sheet were implemented in the establishment of the engineering model (6). The geometrical model is parametrized, see right picture in Figure 20, and all the features from the KBS elements have to be integrated and connected to the geometrical model.

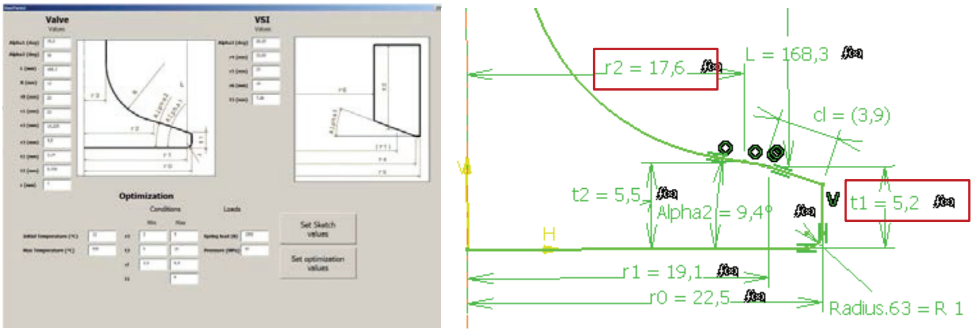
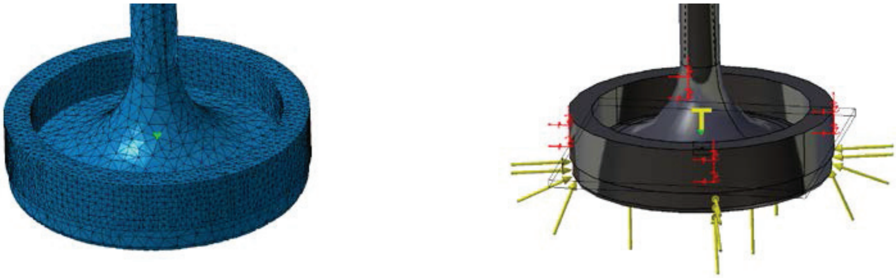


Figure 20. User interface, left and parametrized geometric model of the exhaust valve seating design, right.

Establishment of the computational model (7) prepares for the analysis execution and introduces the necessary settings for the analysis. Tolerances of the mesh, boundary conditions and contact properties, and the materials are implemented into the computational model – some of the outputs as presented to the user are illustrated in Figure 21.

Under the detailed planning of the task (8), the final settings for the model are agreed upon. An agreement on how the user should utilize the template involving sub activities (9) is now completed.

The computational model is now ready for solution and the solution scrutinizing (10) is performed. Note that during this activity the method development involves a number of analyses in order to fully manage all possible solution outcomes. When developing new methods, especially if they are going to be used by less experienced engineers, it is important that the solving process (11) is adapted in solving time and problem size, and supervision of the solving process, evaluation of the computational model for constituencies and other issues that can arise during the solving process. Under the extraction of solution results (12), "sensors" (extreme values in form of parameters) and predefined plots are implemented. The sensors are also utilized for assuring the quality, by comparing the result with the agreed settings for the specific task. If any values are outside the valid range, warnings appear, informing the user that the given solution is not valid. With this type of method development, consistency of both the geometrical and the computational model is important. A number of different computations are performed for validation of the developed template (13). During the same phase an extra validation is performed with external analysis software. After the verification has been completed, task documentation (14) is made, containing the full process of the method development as well as the background information on its purpose. As the developed template is meant to be used by different users, a user guide (15) is written to support the engineering designer while performing analysis by using the template. The last sub activity in the method development is finalizing the method development (16) and implementing the template (17) for use in the engineering design process. The outline of the workflow of the method development of a template for the design analysis of exhaust valve seatings is seen in Figure 22.



The engineering model – mesh

The engineering model boundary conditions

			Conditions		Loads	
			Min	Max		
Initial Temperature (°C)	12	**r3**	3	5	**Spring load (N)**	1500
Max Temperature (°C)	550	**t3**	5	10	**Pressure (MPa)**	30
		d	3,5	6,5		
		t1		6		

Table of the settings

Figure 21. Some outputs from the template.

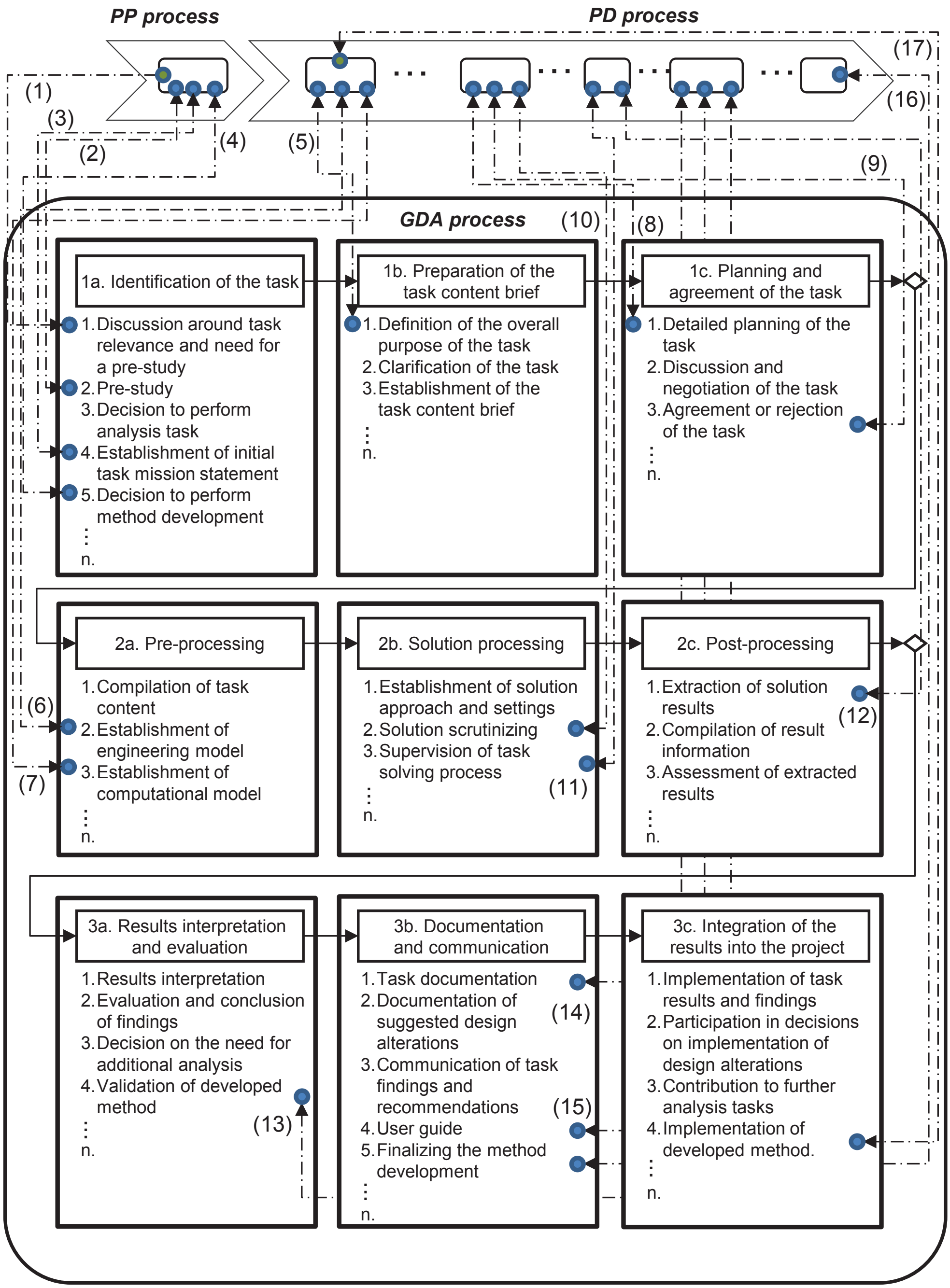


Figure 22. Workflow of the method development of a template for the design analysis of exhaust valve seating’s.

6 Concluding remarks

The objectives initially established for the GDA process model presented in this paper article might be condensed as follows:

- The developed process model should facilitate the interactions between the design analysis (CBDA) process and the engineering design processes on an operational level.
- The process model should be implementable in industrial practice as well as in the training of new generations of analysts and engineering designers.
- The process model needs to be both adaptive and generic; here to be interpreted as not being dependent on any specific engineering design process model and on any specific type of product.
- Applications of the developed process model should be performed in order to, as fully as possible, validate the process model and to gain incentives for further development of it.

The GDA process model accommodates interaction with the engineering design activities and process on all levels of abstraction. In terms of process and activity elements, the GDA process model provides such an interaction on three levels of abstraction corresponding to the phase, activity and sub activity levels. From the applications of the GDA process model in industrial practice, it is found that these levels of abstraction are adequate to match the corresponding levels of activity and process elements within the engineering design activities and processes on an operational level, and thus they are also fit to match the textbook process models on an operational level; in industry, as previously mentioned, the textbook process models are used as platform models upon which adapted process models are built. Regarding the interactions between the engineering design activities and processes and the overall processes, these are already accounted for within the structuring and couplings of these process models. The level of abstraction of the product-to-be, or stage of development of the product, does not cause any problems due to the inherent nature of design analysis process.

From the application of the GDA process model in industrial practice, no problems have been found indicating difficulties regarding the implementation of the process model. However, the GDA process model has not yet been utilized in formal education and training of engineers, as such an undertaking requires substantial insights from the engineers to fully understand and be able to utilize the engineering design process model and related processes models within the industrial enterprise in which they are working. It might be easier to introduce the GDA process model subsequent to the teaching of engineering design process models in formal education.

The required adaptivity of the GDA process model is sufficiently accounted for by the matching on all levels of abstraction, as described above, as well as the by the neutral formulation of the contents of each activity and process element in the GDA process model and the adaptation of a terminology matching that of the engineering design process and its overall processes. The similar elements also contribute to fulfil the generic nature of the GDA process model.

As pointed out in the introduction of the application projects presented, publication of industrial projects is usually not allowed in full detail. This is also valid regarding the application examples presented in this article. An inevitable outcome of constraining publication in this way is the problems arising for providing all the information necessary for validating the process model. This is due to the fact that it is very complicated, if not impossible, to exclude the often fuzzy and sometimes irrational and unexpected factors inflicting complications in a real world industrial project. However, some of the aspects of such a validation are already accounted for above. In addition to these aspects it is interesting to observe that the use of the GDA process model provides excellent possibilities to more or less fully describe a workflow during a design analysis task in detail. The potentials for using this information to extract specialized process models to fit specific contexts are evident. The access to such models might become a powerful planning tool as well as provide the means for supervision and control of such projects.

The GDA process model presented is the first version of the model. A revision of the process model is expected to be done when additional application information is at hand, and preferably then also including training and education experiences. Closer in time is an implementation of a database system to facilitate the handling of the workflows, also including those within the engineering design process and thus significantly contributing to make the GDA process model more user-friendly and useful, especially in industrial practice. This implementation also provides a number of possibilities to analyse specific parts of the workflow such as: bottlenecks, abnormal costs for specific activities, hardware and software problems and opportunities etc.

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Paper V

Development of a computer-aided fixture design system for lightweight grippers in the automotive industry

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Development of a computer-aided fixture design system for lightweight grippers in the automotive industry

Abstract

The need for dedicated fixtures for flexible manufacturing systems is increasing, as dedicated fixtures are lighter, more compact and, more accurate than flexible fixtures. The main challenges are that parts and processes are becoming more and more complex, which requires designing novel or complex dedicated fixtures, and that, for one given flexible fixture to be replaced, several variants of such dedicated fixtures must be designed to hold a variety of individual parts, without causing increased costs and delays. The systematic fixture design method and computer-aided fixture design system (CAFDS) developed and applied for the presented industrial case—novel design of a lightweight (carbon fibre composite) robot gripper—is a possible approach to addressing these issues.

Keywords

computer-aided fixture design; CAFD; fixture design; dedicated fixtures; grippers; end-of-arm tools; automated assembly; automotive industry; flexible manufacturing systems; FMS; robotic cell; knowledge-based engineering; KBE; concurrent engineering

1 Introduction

The automotive industry in general is facing the double challenge of developing and releasing new product versions at an ever-growing pace and of allowing increased customization of their products. These challenges put enormous strain on the production system, which must be flexible while at the same time aiming for the efficiency and competitive cost of a mass-production system. In that context, the development of adequate fixtures is an important part of process planning: at the interface between the workpiece and the manufacturing equipment, they are a “crucial” element for the flexibility of the manufacturing systems (Causey, 2003). They also represent 10-20% of the manufacturing system costs according to Bi and Zhang (2001).

A fixture consists of a set of elements that hold, support and clamp a workpiece during manufacturing operation(s). Fixtures can be roughly categorized into dedicated, flexible and universal (general-purpose) fixtures. Dedicated fixtures are designed for a particular workpiece, flexible fixtures can hold a variety of individual parts while universal fixtures are universal work-holders such as chucks, vices and the like, used for workpieces of simple geometry (Hargrove and Kusiak, 1994). Dedicated fixtures have been used mainly for mass-production systems, and with the movement towards flexible manufacturing systems (FMS) most research within fixture design has dealt with flexible fixtures systems (An et al., 1999) as they are reusable, thus decreasing costs and lead time (Bi and Zhang, 2001; Boyle et al., 2011; Hargrove and Kusiak, 1994; Kang and Peng, 2009).

Nevertheless, new demands are calling for the qualities of dedicated fixtures even for FMSs. The workpieces have more often complex geometries (Wang et al., 2008) which makes it difficult to plan for flexible fixtures. There is also a demand for increased accuracy (Rong et al., 2005, pp. 95-96). The functions and working principles of the fixtures are themselves becoming increasingly complex, see e.g. (Li et al., 2010). Moreover, functions such as guiding and graduating are less necessary because of the advanced manufacturing systems (Rong et al., 2005, p. 96). Many fixtures are also used by robots or transported with the workpiece, and in that context weight becomes critical: cycle times are dependent on the weight of the gripper and workpiece (Choi and Ip, 1999), a lighter gripper therefore reduces cycle time; lighter grippers also allow for the use of smaller, much cheaper, robots. It is therefore increasingly necessary to resort to dedicated fixture components.

The main challenges—beyond the obvious drawback that a dedicated fixture needs to be re-designed for each new version of a product part—are 1) that parts and processes are becoming more and more complex, which requires designing novel or complex dedicated fixtures, and 2) that, for one given flexible fixture to be replaced, several variants of such dedicated fixtures must be designed to hold a variety of individual parts, without causing increased costs and delays.

The first challenge regards the fixture design process. The design of a fixture in general (dedicated or flexible) is considered a complex, intuitive and ad-hoc process (Kang et al., 2007, p. 143; Wang et al., 2008, p. 848), that requires extensive experience and even expertise—10 years or more of manufacturing practice according to Rong et al. (2005, p. 96).

Accordingly, fixture design is seen as incremental, based on earlier designs (Rong et al., 2005, p. 99). However, for novel or complex fixtures, that is, fixtures that require new working principles or materials, the traditional, incremental fixture design approach needs to be enhanced to enable the development of new concepts.

Regarding the second challenge, supporting the design of variants of fixtures, a large body of research has been dedicated to the development of computer-aided fixture design systems (Bi and Zhang, 2001; Boyle et al., 2011; Cecil, 2001; CAFDS, Hargrove and Kusiak, 1994; Kang and Peng, 2009; Pehlivan and Summers, 2008; Wang et al., 2010). Such systems exist for both dedicated and flexible fixtures. However, there is a lack in supporting the design synthesis of the fixture (Boyle et al., 2011, p. 10), which is a critical issue for complex dedicated fixtures.

In this paper, the systematic fixture design method and CAFDS developed and applied in the context of an industrial case, the design of novel, dedicated, lightweight grippers for robots, are reported. The industrial case has several distinctive features. There were rigorous requirements on e.g. weight reduction and on tolerances, and after due consideration of alternative materials it was decided that carbon fibre material should be used; The production engineers, traditionally responsible for the design of fixtures, did not possess the knowledge and competence needed for carbon fibre design and analysis. The CAFDS therefore had to target the specific needs of the fixture designers, an aspect sometimes neglected in fixture literature (Hargrove and Kusiak, 1994, p. 749). Moreover, the CAFDS had to be integrated in the concurrent engineering environment (exchange of information between the product development team and the process development team), a theme that has also been less systematically addressed in fixture design research (Pehlivan and Summers, 2008, p. 791).

The paper is outlined as follows. The next section presents the problem definition: the fixture function in the prototype production cell and the company's fixture design process in which the CAFDS is to be integrated. The process model for the design of the novel dedicated fixture and its CAFDS are presented next. The design of the lightweight gripper is then detailed, with emphasis on conceptual design. Finally, the architecture and process of the CAFDS of the lightweight gripper are described and illustrated.

2 Problem definition

2.1 The fixture function

This section describes the operative environment of the fixture, the requirements it must fulfil, and the reasons why a dedicated fixture as well as a CAFDS were necessary.

In the prototype production cell of the truck cab assembly, all sheet metal parts constituting the body-in-white (BIW) of the cab are both transported, positioned, and attached with the help of the robot gripper before being joined together by spot welding to secure the cab's geometry.

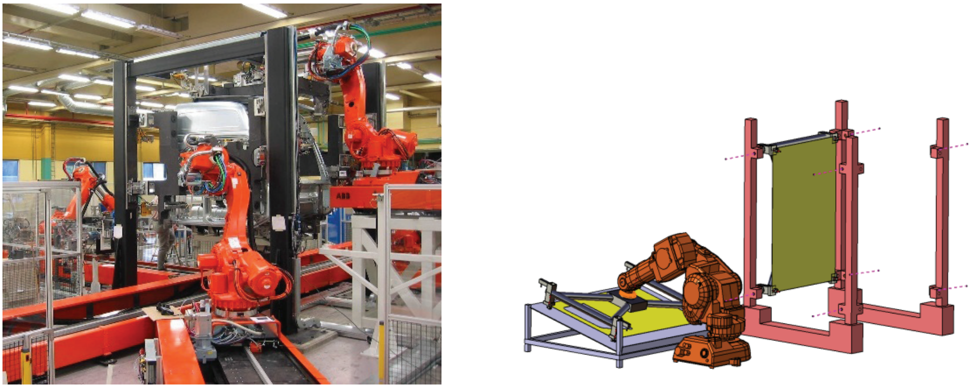
The production cell is patented (Eriksson and Wallengren, 2001); the complete handling process is represented in Figure 1.

Traditionally these grippers are built around a gripper base usually made of steel. On this gripper, base clamps, locators and adjustment boxes are added, all of which are needed in order to accommodate the subsequent assembly operations. Such grippers are rather heavy and thus restrict the allowed weight of the workpiece for a robot of a given size. With an expected increase of production rates, the current robotic equipment was facing diverse problems during transportation and alignment of the sheet metal parts, problems related to mass inertia, accuracy, stability and the combined weight of gripper and sheet metal part. The solution was either to upgrade the production system with more powerful robots or to develop lighter fixtures. The latter alternative was chosen due to lower acquisition costs and the fact that the robot in question was the only one which could also be equipped with a fully integrated spot welding device.

The new grippers should also provide enough flexibility to accommodate current and foreseeable sheet metal parts, contribute to improved tolerances in the assembly operations, as well as eliminate or significantly reduce the need for frequent calibrations, and contribute to an increased ratio of production capacity.

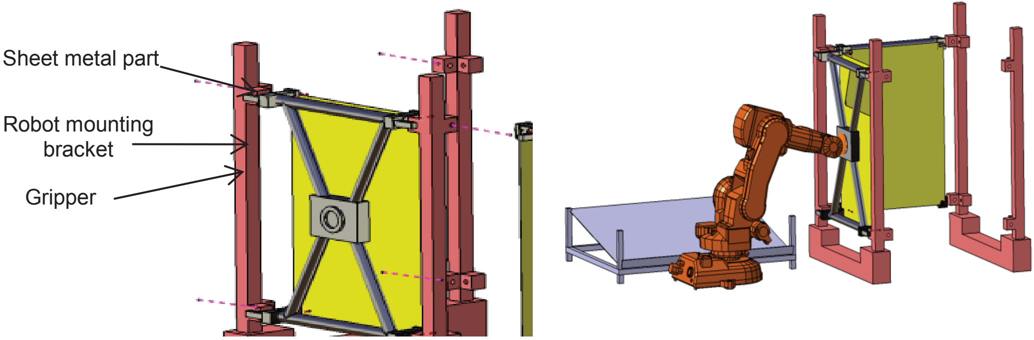
Carbon fibre composite was chosen as a solution to fulfil the requirement for the grippers to be lightweight and simultaneously providing the required stiffness to fulfil the requirements set out for the tolerances. Carbon fibre composite is a material with specific properties that greatly complicate fixture design. Moreover, it is very difficult to develop modular (flexible) fixtures in carbon fibre composite because of the difficulties in interfacing such elements with others. Therefore, dedicated fixtures were the only possibility.

Finally, customization of the trucks requires rapid development of an appropriate fixture. It was therefore necessary to have computer support for fixture design.



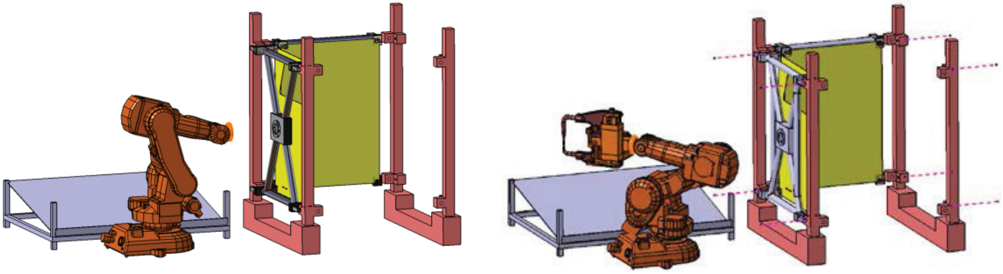
a. The production cell

b. Robot picks up the sheet metal part from the stack



c. The gripper is aligned to the support frame

d. The gripper is attached to the support frame



e. The gripper is disconnected from the robot

f. The robot is equipped for spot welding

Figure 1 a) Production cell; b-f) Illustration of the sequence of handling operations for one of the six robots of the production cell. After disconnecting the gripper, the robot picks up the spot welding equipment and starts the welding process.

2.2 The gripper design process in the concurrent product and process development environment

Figure 2 presents the different steps of the truck cab development process concurrently with the gripper design process. The truck cab is developed by the company at one site, and the production engineers, responsible for process development, operate at another site. As the figure implies, the CAFDS must ensure that fixture planning and fixture design respond dynamically to product design changes. The advanced design analyses of the gripper are represented separately, as they are performed by the design analysis department.

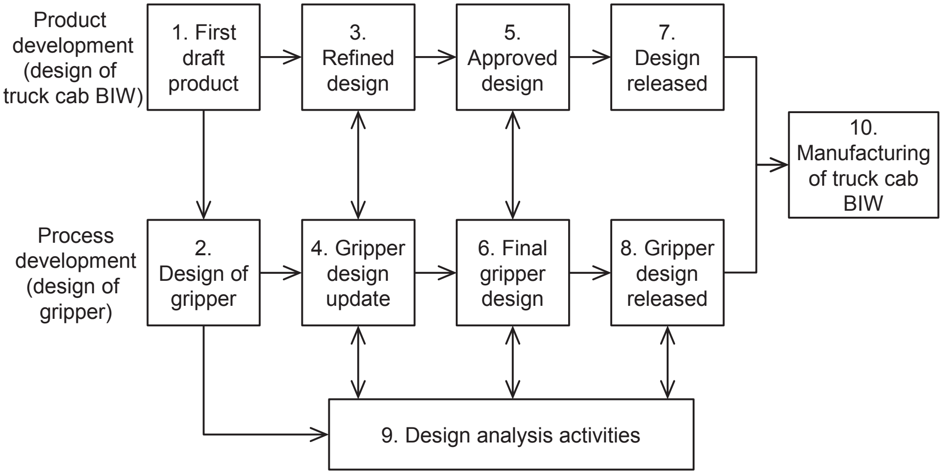


Figure 2 Design of truck cab BIW and gripper within the concurrent product and process development environment

3 Process model for the design of the fixture and the CAFDS

3.1 Fixture design

Although some variations exist among authors, there is a large consensus about the fixture design process outline, see e.g. (Bi and Zhang, 2001; Boyle et al., 2011; Kang and Peng, 2009; Rong et al., 2005). There are four main stages:

a. *Setup planning:* A setup defines the product features from the manufacturing operations that can be performed on a workpiece without having to alter the position or orientation of the workpiece manually (Boyle et al., 2011, p. 4). Setup planning is the determination of the number of setups, the position and orientation of the workpiece in each setup, and manufacturing and assembly in each setup, (An et al., 1999) from (Rong et al., 1997).

b. *Fixture planning:* determination of the locating and clamping points on the workpiece (Ma et al., 1999, p. 171).
c. *Unit design:* full determination of the fixture element and layout including design analyses: deformations, tolerances, collision analyses, etc.
d. *Verification:* more extensive design analyses are carried out: structural integrity analysis, stability analysis, etc.

Steps *a*, *b* (which correspond to defining the requirements) are well established (Bi and Zhang, 2001; Boyle et al., 2011; Kang and Peng, 2009; Rong et al., 2005). However, they do focus on traditional usage of fixture, and are not adapted to the identification of other requirements. For example, what is unique for grippers, in comparison with other types of fixtures, is that there is a workpiece transportation moment. In order to secure a systematic establishment of all requirements, it is necessary to go through the whole product lifecycle, and for each phase of the lifecycle study possible interactions between the product, its environment and the people involved and their economic implications. Requirements resulting from these interactions are then listed. The method used for such a systematic requirement investigation is POME (Olsson, 1995), also called the 'Olsson table' (Schachinger and Johannesson, 2000). In POME the artefact to be specified is considered as a technical system (Hubka and Eder, 1988) performing a *process* in an *environment*, possibly interacting with *humans* (directly interacting with and/or affected by the product), and with *economic* implications. The potential interactions between the different system elements (process, environment, humans, economic implications) are studied along the whole product lifecycle (development, production, distribution, use, termination), and requirements are listed for these interactions.

The conceptual design part of the fixture design process in step *c* has been less completely developed. As was mentioned earlier, it is considered incremental and experience-based (Kang et al., 2007; Rong et al., 2005; Wang et al., 2008). It is also asserted in (Rong et al., 2005, p. 99) that "for a more complicated fixture design, new design requirements are typically met by adapting an existing design." This is not always possible for novel fixtures. In order to be able to design new fixtures effectively and fairly quickly it is necessary to adopt a more systematic approach.

For the unit design of a fixture, the process makes use of the general problem solving process that is one of fundamentals of systematic design (Hubka and Eder, 1996; Pahl et al., 2007):

1. problem analysis and clarification,
2. systematic concept generation and refinement,
3. design analysis and evaluation, and
4. final selection.

In the problem analysis step (1) the essential problems are identified and analysed (for example more information and tests would be required regarding carbon fibre composites).

The concept generation step (2) in the engineering design literature (Eder and Hosnedl, 2010; Pahl et al., 2007; Ullman, 2010; Ulrich and Eppinger, 2012) often focuses on defining the product's functions, finding new working principles (use of different physical effects to achieve a particular function), and combining them to find the best possible solution principles. For several types of product, this is not a necessity (Franke, 1979; 1985; Motte, 2008). For example, functions and working principles are well defined in the case of the design of large-scale pumps (Franke, 1979, p. 79). An alternative, possibly complementary, view of the concept generation step is to consider it as an uncertainty reduction step, see e.g. (Cross, 2008). A conceptual solution should be free from high technical (and marketing) risks in order to give confidence in investing into the later, more expensive design and development stages. Design of the technical system's layout and form, that is embodiment design and even in some cases some detailed design, might therefore be included in the conceptual stage if they present high uncertainties. This goes for many fixtures where the function and working principles are the same across fixtures, but the layout and form are challenging in terms of design. The notion of concept design in the development of fixture is therefore extended to include the investigation and design of the product features that present high uncertainties.

Finally, for the analysis and evaluation step (3), special care needs to be given to the design analysis (for example, structural analysis such as finite element analysis, FEA) and its associated constraints (time, resources, use of companies' standards, confidence level for the result, etc.). These constraints need also to be systematically determined
(Eriksson and Motte, 2013; Petersson et al., 2012).

The fixture design process is shown in Figure 3. The basic fixture design steps are enhanced by the elements presented above. Note that although steps *c*2, *c*3 and *c*4 are represented sequentially they are sometimes done simultaneously.

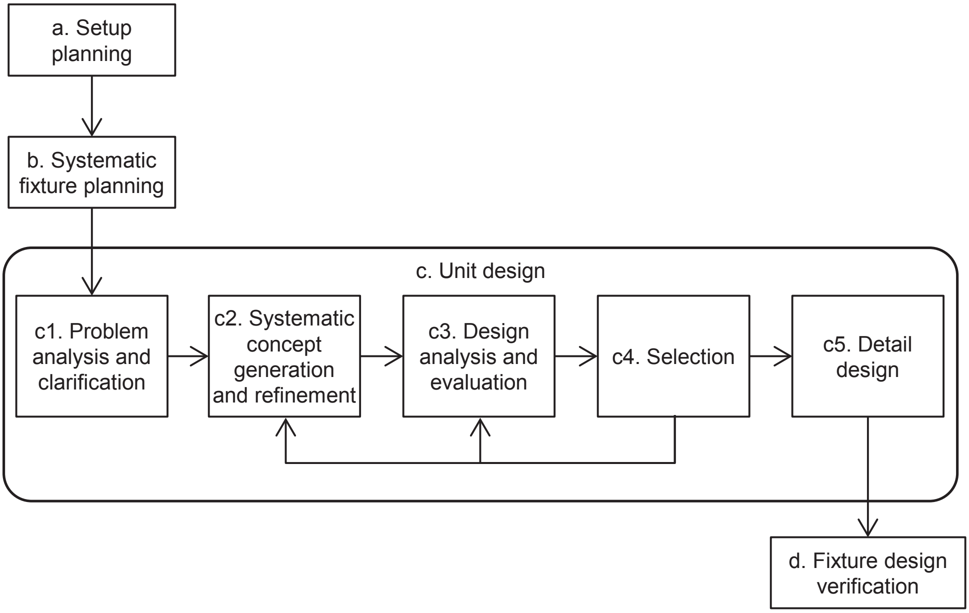


Figure 3 Fixture design process model

3.2 Computer-aided fixture design

A CAFDS is a computer-based system automating the fixture design activities (Cecil, 2001, p. 790). Each variant of a part will require a specific design of its fixtures. It is therefore necessary to automate as much as possible in this step, based on the fixture elements determined during fixture design.

The development of a CAFDS requires taking into account as much as possible the different cases that the system might encounter. CAFDSs for dedicated fixtures have specificities, in comparison with systems for modular fixtures. As noted in (Rong et al., 2005, p. 103), although fixtures can be entirely customized, this is rarely the case in practice. The dedicated fixtures usually have standard clamps, locators and adjustment boxes; only the fixture base needs generally to be custom-made. A typical CAFDS for dedicated fixtures will therefore consist in a library of standard fixture components, a library of custom-made fixture base models and a fixture component relationship database where the information of how to connect the fixture components together is stored.

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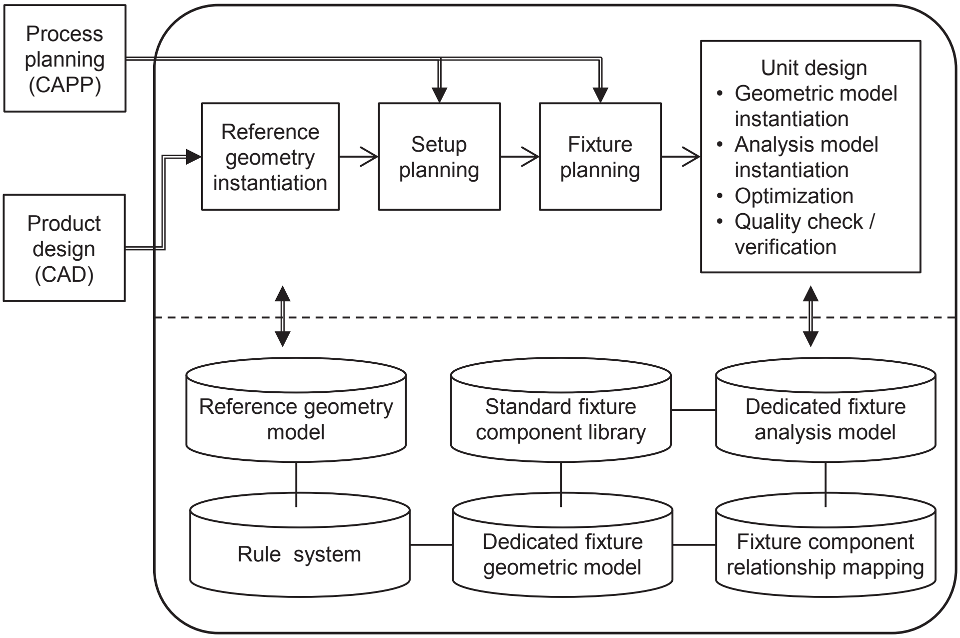
The design of the dedicated fixture base models can be quite complex. Moreover, it might be necessary to make complementary analyses (structural, tolerances, etc.) and optimization. The dedicated fixture library then needs to include both geometric and analysis models of the fixture.

In a concurrent engineering process, the systems need to be able to extract relevant information from the reference part model in order to use this information in the setup planning, fixture planning and unit design step. Therefore, a corresponding reference geometry model needs to be present in the CAFDS.

Finally, in order to achieve all these connections, a knowledge-based engineering (KBE) framework is required. By definition, a KBE system is "a usage of suitable computer software for acquiring and reusing knowledge on a product and process in a possibly most integrated way", (Skarka, 2007, p. 677) from (Stokes, 2001). KBE systems have previously been successfully developed for automated design and analysis of products and manufacturing tools, see e.g. (Callot et al., 1998; Chapman and Pinfold, 2001; Johansson, 2011). Therefore, the CAFDS must in such cases be complemented with a rule system.

Drawing on Rong et al. (2005, pp. 97, 102) and Boyle et al. (2011, p. 3) and the above, the CAFDS model is illustrated in Figure 4.



Title

Figure 4 CAFDS process (top) and elements (bottom) for a complex dedicated fixture

The following sections report the fixture design of the lightweight robot gripper and development of its CAFDS, which illustrate the fixture design process and CAFDS models presented.

4 Fixture design of the lightweight robot gripper

4.1 Setup planning

The fixture is involved in the following operations (see Figure 1): the robot picks up the sheet metal part from the stack with the help of the gripper, the gripper is then aligned to the support frame, and subsequently attached to it, before the welding of the BIW structure can start. As all sheet metal parts of the BIW are welded to each other simultaneously, there are very tight position tolerances from the origin of the global vehicle coordinate system, comprised in a 0.1-0.3 mm interval, which is small in comparison with the size of the sheet metal parts (about 2500×2500 mm).

4.2 Systematic fixture planning

The requirements were mainly identified through interviews with the workers utilizing similar grippers on a daily basis. The workpiece presents 4 or 6 holes for the locators, always positioned at a certain distance from the workpiece contour so that the clamp positions can easily be determined (correspond to the points at the periphery of the sheet metal part in Figure 13). Also, specific analyses were carried out for the transportation moment in order to determine the centre of gravity and moments of inertia of the gripper and workpiece (and hence the maximum weight of the gripper), given that the robots would move at a quite high speed (heavier grippers would require a stronger and much more expensive robot). Likewise, diverse tolerances were established: holes in the grippers to allow quick fixation to the robot, and holes in the workpieces to allow quick positioning of the gripper's locators.

The main requirements are listed below (the complete list of requirements is reported in (Petersson, 2008)):

- Weight of gripper base must be minimized and cannot be more than 30 kg,
- Static deformation < x mm (proprietary information),
- Dynamic deformation no more than twice the static deformation,

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- Weight of fully equipped gripper < 175 kg,
- Distance between the centres of gravity of the gripper, the sheet metal part and the robot mounting bracket must be minimized in order to minimize inertia forces during transportation of the complete gripper and sheet metal part,
- Access to welding equipment.

4.3 Unit design

4.3.1 Problem analysis and clarification

A first version of the gripper in carbon fibre composites had been developed prior to the start of this project (Strömberg, 2009). It was based on the design of the existing gripper (as is traditionally done within fixture design, cf. above). This gripper did not fully utilize the potential of the carbon fibre material as it should because of all the cut-outs and holes in the fibres (see Figure 5), and it proved necessary to design a new version from scratch, see (Werius, 2008).

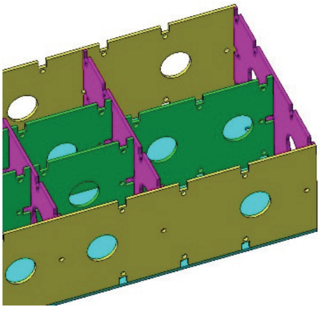


Figure 5 Detail of the first version of the lightweight gripper

The specific properties of carbon fibres made the search for a suitable concept very extensive. Detailed modelling of the behaviour of the fibres would make design analysis and optimization far too time-consuming. It was also necessary, both for structural design analyses of different concepts and for the built-in design analysis model in the CAFDS, to utilize a simplified but still representative constitutive model of the behaviour of the carbon fibre material. Therefore, standard uniaxial tensile tests of carbon fibre specimens with woven carbon fibres in the directions 0, 45 and 90 degrees relative to the width of the specimen (rectangular cross section) and a thickness of 3 mm, were performed to find a constitutive model that gave satisfying results. The properties of the carbon fibre material in relation to specific geometric alterations (holes and diverse cut-outs) were also tested, see Figure 6.

Figure 6 Test specimen (150 × 49 mm plate with hole of Ø20 mm) to establish material behaviour

The stress strain relationship is more or less linear as can be seen in Figure 7. Design analysis models with the representative carbon fibre definition were established, and the results are included as dots in Figure 7. The results show quite good agreement for the simple test specimen in the range of a couple of percent. For the specimen with a hole the difference is somewhat higher, 10-40 percent, which must be taken into account when considering the final design solution. However, the overall conclusion is that an isotropic materials model, such as for example an aluminium one, represents the almost linear stress strain relationship quite well when utilized in back to back comparisons between different design concepts.

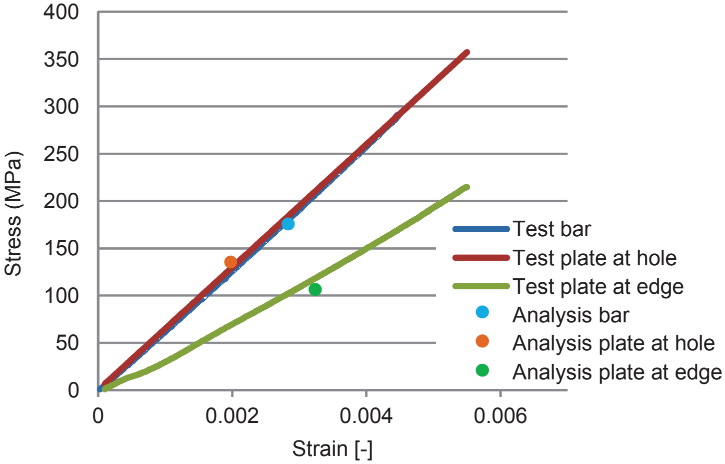


Figure 7 Stress strain relationship in the performed physical testing

4.3.2 Systematic concept generation, analysis and evaluation

Several layouts (20 or so) of the gripper base were generated and analysed. Basic shapes of four of the investigated concepts are shown in Figure 8.

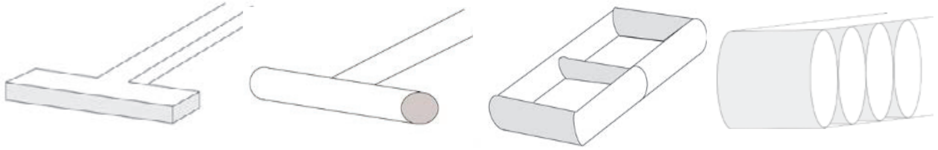


Figure 8 Models of four different concept proposals (concepts 8, 9, 11 and 19)

Three load cases were considered for different uses of the gripper: aligning the gripper to the sheet metal part placed in the stack (Figure 1b), transporting the gripper with the BIW element from the stack to the main frame (Figure 1c), and aligning the gripper to the side of the main frame (Figure 1d). See Figure 9 for a schematic view of the concepts. The results extracted and interpreted were weight, deformation, stress distribution and buckling resistance, all related to the requirements listed above.

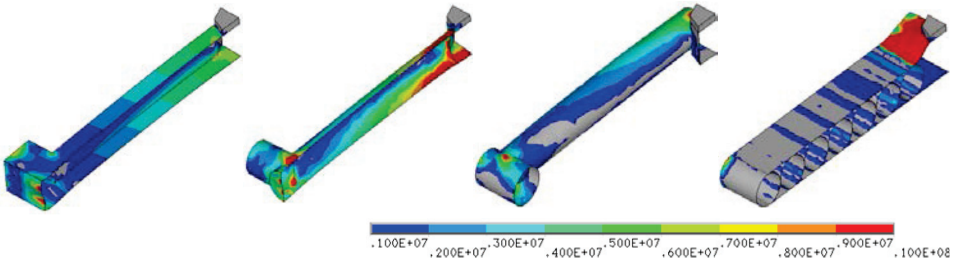


Figure 9 Von Mises stress plots (N/m^2) of the four different gripper base concepts (symmetric models, quarters of the full part), with loading applied at the gripper clamp while the robot mounting bracket was fully constrained

In the overall assessment of the potential solution, weight, deformation and stress were considered as equally important and given an evaluation factor of 0.3 while the buckling was given a factor of 0.1. The study revealed that simple beams with rectangular or round cross sections made the best utilization of the carbon fibre properties, as can be seen in Table 1.

Table 1 Results evaluation from bending load case with overall ranking of the four different concepts

Title

Concept	*Weight*	*Deformation*	*Stress*	*Buckling*	*Overall sum*	*Ranking*
8	3	1	1	12	2.7	1
9	1	5	12	10	6.4	3
11	7	2	3	19	5.5	2
19	19	8	9	4	11.2	13

4.3.3 Final selection, detail design and verification

This resulted in a final concept consisting in a combination of two concentric hollow boxes that support and stabilize the robot mounting bracket and the beams onto which locators, clamps and adjustment boxes are fixed. Such simple beams can be bought prefabricated, which dramatically reduces fixture manufacturing costs. Figure 10 shows possible configurations of the gripper base. The locators, clamps and adjustment boxes to the support frame of the production cells are positioned at the extremities of the gripper base (compare Figure 1). The double beam system of each “arm” of the gripper base allows the generation of fixtures for any possible size of the workpiece, production cells and their respective contact points.

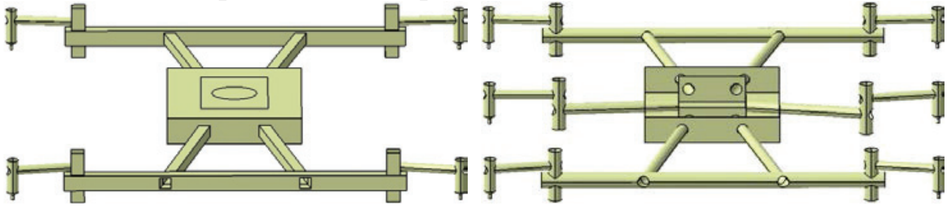


Figure 10 Possible configurations of the gripper base (left: base made of rectangular beams; right: top panel of the gripper base removed to display the concentric hollow boxes and base made of cylindrical beams**)**

For the beams, to which the clamps, locators and adjustment boxes are attached, standardized product forms (sizes) are used for cost reasons. These beams are joined together through a mechanical locking principle, as shown in Figure 11 (left), which facilitates the manufacturing of the adhesive joints and thus reduces the risk of delamination of the carbon fiber. The mechanical locking principle is developed in (Petersson et al., 2013). The clamps, locators and adjustment boxes are standard fixture components bought from a supplier. They are always at the same position on the gripper base, see Figure 11 (right).

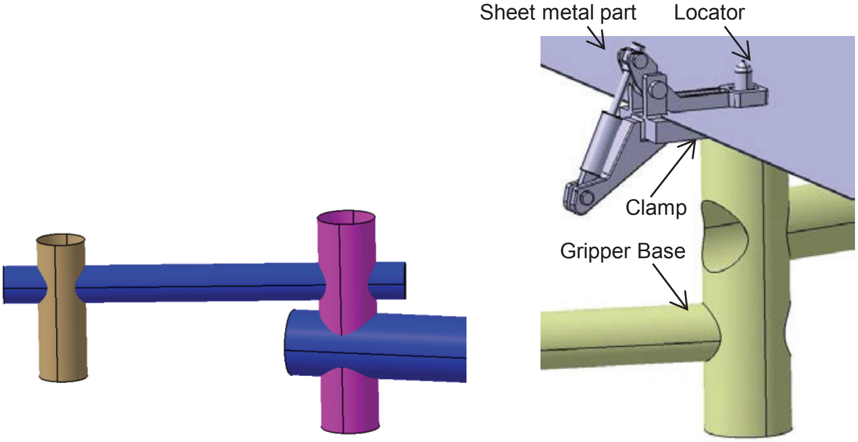


Figure 11 Left: Mechanical locking; right: Standard clamp and locator on the gripper base (adjustment boxes not represented)

5 The CAFDS

For the present project, the KBE framework allowed for the present project to automate most of the design process of the gripper and to integrate rules in software elements such as CAD and FEA programs.

This section presents: 1) further requirements specific to the industrial case, 2) the CAFDS architecture, 3) the CAFDS process, 4) its implementation, and finally 5) each element and 6) each step of the CAFDS in a more detailed way.

5.1 Further requirements for the CAFDS

The design of the gripper is the responsibility of the production engineers; therefore, special care needs to be taken regarding the user-friendliness of the CAFDS.

The CAFDS does not provide full design analyses of the final grippers (such as detailed structural integrity analysis and stability analysis), as they require interpretation by an expert (cf. Figure 2). To that end the CAFDS must present relevant output for the subsequent evaluations. At the same time, the quality of the design analysis performed by the CAFDS must be ensured so that the fixture designer has confidence in the fixture that is handed over for verification and validation.

The CAFDS is intended for use during the different steps of the concurrent development of the BIW and fixtures.

The CAFDS has to be compliant with the truck company's CAD/CAE system (Catia V5), so that it can be fully integrated into the concurrent development of the BIW (cf. Figure 2).

5.2 Architecture

The CAFDS is organized around 3 main elements: the reference geometry model, the fixture geometric model and the fixture analysis model.

The reference geometry model contains input information about the BIW design (geometry, centre of gravity), about the support frame and also about the robot mounting bracket.

The fixture geometric model contains all information about the geometry of the gripper: the different parts and the rules about their possible configurations. There are only a few types of clamps, locators and adjustment boxes. Therefore the standard fixture component library and the fixture components relationship mapping are integrated in the dedicated fixture geometric model (cf. Figure 4).

The fixture analysis model contains the information necessary to define and perform the structural design analysis: material properties, mesh discretization, boundary conditions and load cases.

The KBE rule system is integrated in these 3 elements.

5.3 Process

When the reference geometry is obtained, the CAFDS automatically generates a fixture geometric model that fits the reference geometry, and a fixture analysis model. The user then introduces the optimization features. Once the gripper base has been optimized, a post-processing analysis of the variant is performed (quality check).

The process and architecture of the CAFDS are presented in Figure 12 and detailed in the next section.

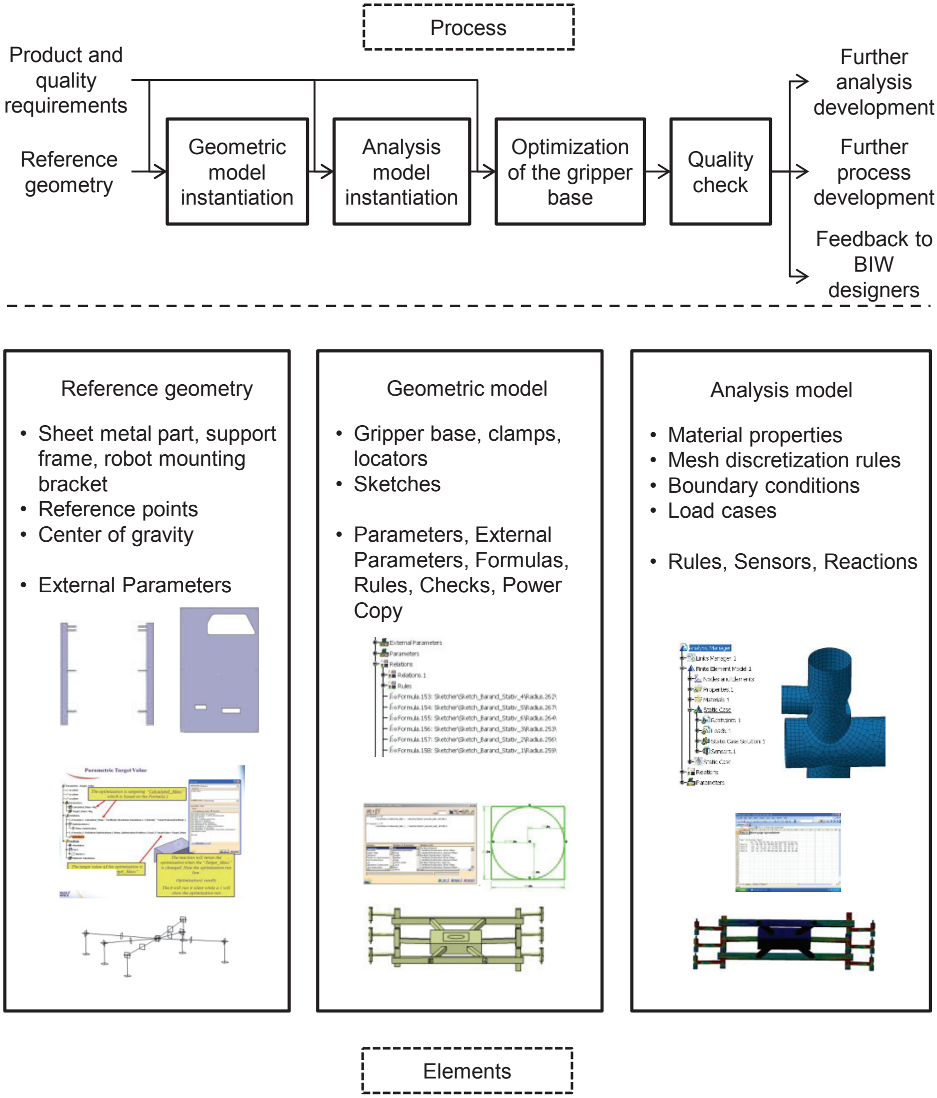


Figure 12 The CAFDS process and architecture

5.4 Implementation

The CAFDS has been implemented using Catia V5’s KBE system Knowledge Ware (Knowledge Advisor and Product Engineering Optimizer) and its FEA software (Generative Structural Analysis and Advanced Meshing Tool modules).

Table 2 presents the number of knowledge-based features implemented in the CAFDS.

Table 2 Number of implemented knowledge-based features

External References	18	Rules	24
External Parameters	10	Checks	8
Parameters	30	Power Copies	3
Design Tables	4	Reaction	1
Formulas	242		

5.5 Elements of the CAFDS

5.5.1 Reference geometry

The reference geometry consists in reference points and surfaces from the sheet metal part, support frame and robot mounting bracket, as well as information about their centre of gravity (Figure 13). This will be used together with the fixture geometric model to instantiate the gripper base geometry.

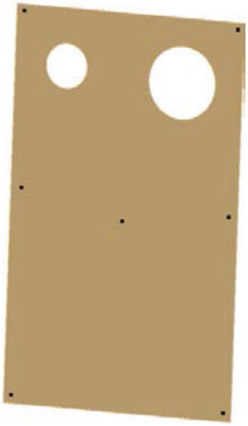


Figure 13 The sheet metal part with reference points, including the centre of gravity (the real geometry of the sheet metal part is proprietary information)

5.5.2 Fixture geometric model

The fixture geometric model must fulfil several functions: it must enable instantiation of the gripper from the reference geometry, it needs to be compatible with the constraints of the FEA, it must be able to evolve during optimization, and it must be easy to manipulate and robust for the production engineer.

The gripper base is modelled as a thin-walled design in order to limit the time required for subsequent design analyses. In all, the gripper base consists of 93 single surfaces. The surfaces are parameterized, and the model is controlled and monitored by a set of formulas, checks and rules so that it can fit the reference geometry and evolve.

As the beams can be either round or rectangular, the two profiles are defined within the same sketch (see Figure 14), and are manipulated through a specific rule.

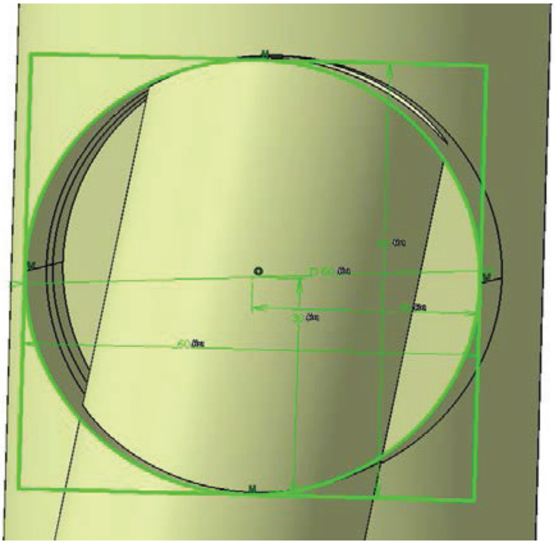


Figure 14 Implementation of the round and rectangular cross sections

The clamps and locators are standard CAD elements. They are used during the geometry instantiation. The adjustment boxes are not represented as they have no role in the geometry instantiation and subsequent optimization of the gripper base. The fixture component relationship mapping is assured by all components being connected by active external references (that is, their spatial positioning is coupled with each other). With this knowledge-based geometric model, the manipulations of the production engineers are minimized.

5.5.3 Fixture analysis model

The fixture analysis model contains information about the material properties, boundary conditions and load cases. All load cases (described in Section 0) are solved within one design analysis setup. A set of sensors (pointers that fetch the design analysis results in specific nodes of the model) is positioned in the neighbourhood of the clamps to obtain stress and deformation data.

The fixture analysis model also contains mesh discretization rules. For the optimization step, coarse mesh is used: element size 4 mm, 1st order (linear) element, geometric representation within 0.2 mm. For an improved geometric representation, 2nd order (parabolic) element is used. Table 3 shows an example of the differences between 1st order and 2nd order meshing for a specific design analysis.

Table 3 Differences between 1st order and 2nd order meshing

	Number of nodes	*Number of elements*	*Degrees of freedom*	*Solving time*[a]
1st order	112,385	112,962	674,310	3 min.
2nd order	337,763	112,962	2,026,578	6 min.

a. Includes time for remeshing the model.

As in the fixture geometric model, a system of checks is implemented to ensure structural integrity and robustness of the fixture analysis model.

5.6 Steps of the CAFDS process

5.6.1 Fixture geometric model instantiation

The fixture geometric model instantiation is the first step of the gripper base design, and aims at generating a first geometry that fits the reference points. The different reference features from the sheet metal part, the robot mounting bracket and the support frame are put together. The centres of gravity of the sheet metal part and the bracket are aligned so that the requirement of mass inertia minimization is respected. Then both are positioned in reference to the support frame (Figure 15). A skeleton is then created (Figure 16).

With the skeleton, the knowledge base defining the gripper base, the component relationship mapping linking the gripper base, and the clamps and locators, a first geometry of the gripper can be generated (Figure 17).

With these elements, the production engineer does not have to manipulate the geometry of the gripper base.

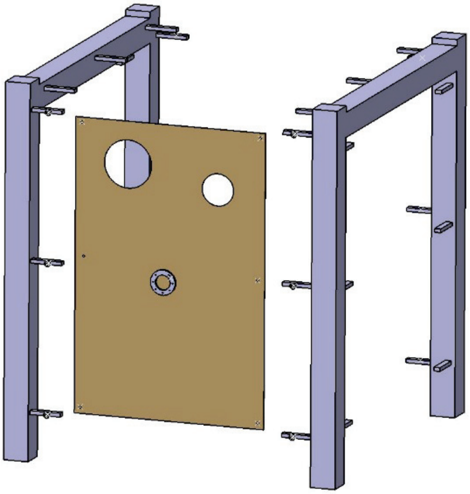


Figure 15 Alignment of the sheet metal part to the support frame and the robot mounting bracket

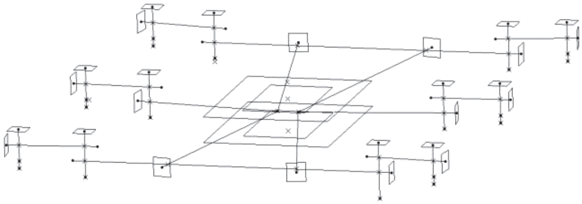
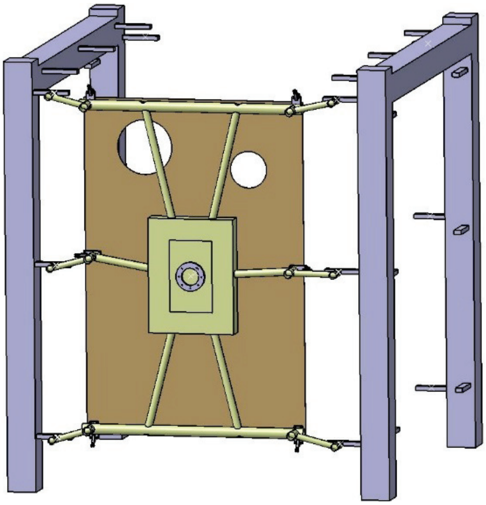


Figure 16 Skeleton



Title

Figure 17 Generation of a first geometry of the gripper

5.6.2 Fixture analysis model instantiation

A fixture analysis model is then built up with shell element mesh on each surface together with assigned physical properties. A first calculation of the model is performed with the objective of establishing all the required input to the subsequent optimization.

After solving the model, the stress and deformation results needed for the optimization are automatically available through the sensors.

The user does not need to carry out any action for this step regarding the evaluation of the model.

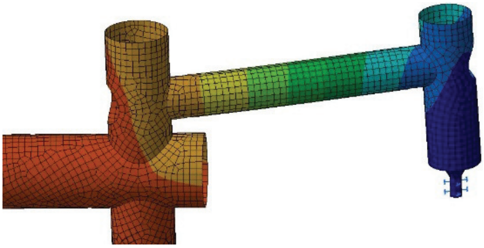


Figure 18 Detailed view of the deformation design analysis result for the gripper base

5.6.3 Optimization

Once a first fixture analysis model is instantiated, the optimization features are introduced by the fixture designer. The optimization constraints are those given by the requirements (maximal possible weights and static deformations…) and by the prefabricated carbon fibre beam supplier. The target value (optimization function) is to minimize the gripper base weight.

Once the optimization has started, it runs without any interaction from the user. The optimization algorithm used is the simulated annealing algorithm integrated in CATIA, whose details are described in (Randelman and Grest, 1986). The parameters of CATIA’s simulated annealing algorithm are the convergence speed and the termination criteria (number of updates without improvement, maximum duration of computation, or maximum number of updates). The convergence speed parameter for the simulated annealing algorithm defines the level of acceptance of bad solutions; if the problem has many local optima, *Slow* is recommended; other configurations are *Medium*, *Fast* and *Infinite* (Hill climbing). The parameters were set to the following: convergence speed = *Fast*, number of updates without improvement = 50 (there was no significant improvement if this value was changed), maximum duration of computation = 300 min., maximum number of updates = 1000 (these last two termination criteria had no bearing on this optimization problem).

The optimization results in beams optimized in terms of cross sections, thickness and diameters are shown in Figure 19. A subroutine rounds the thicknesses and diameters to fit the nearest prefabricated beams from the supplier defined in the CAFDS.

Between 30 and 90 iterations are usually needed to optimize the gripper, which amounts to about 90 to 270 min of solving time.

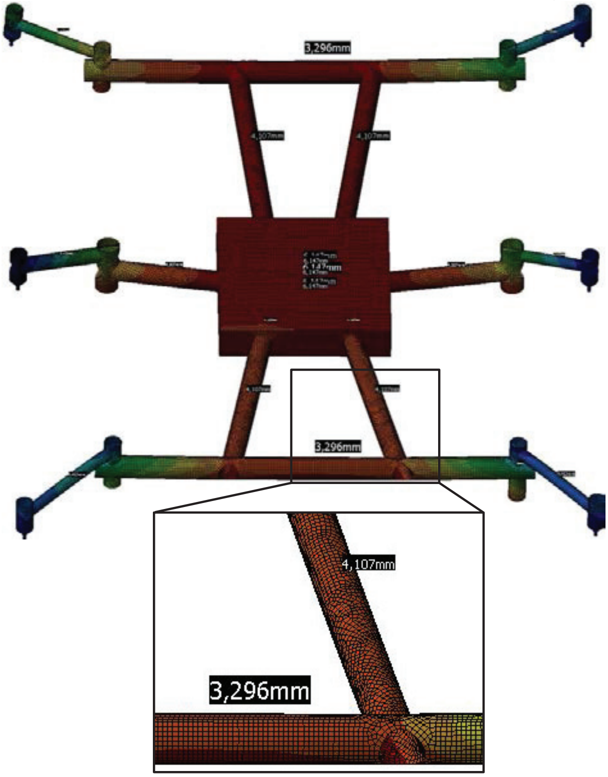


Figure 19 Optimized beam thicknesses prior to rounding

5.6.4 *Quality check*

Finally, a quality check of the final gripper base is performed. The quality check consists in a mesh convergence study, element quality control, reaction force summary together with the assessment of the CAFDS assumptions. Once this final design analysis is performed, the gripper information is handed over to an analyst for a final assessment of the confidence in the performed design analyses and established results. The intermediary results are also handed over to the sheet metal part designers, and the final design to manufacturing (cf. Figure 2).

6 Conclusion

Although flexible fixtures for FMSs are still the norm see e.g. (Saliba et al., 2010), the tendency is clearly towards lighter and more accurate fixtures. There might therefore be a movement towards a renewed use of dedicated fixtures. The generally accepted process model for fixture design needs to be enhanced for complex dedicated fixtures:

- Such complex fixtures are subject to requirements that are usually not taken into account. In consequence, a more systematic requirement elicitation method is needed.
- Their conceptual design requires extensive work. The extra time needed for the conceptual part of the design of the lightweight gripper was about 30 man-weeks. With ever-increasing demands on the manufacturing system, such situations are likely to arise more and more frequently, be it through the use of new materials or of “intelligent fixtures” (Kostál et al., 2011). The design process described above can also be used with additive manufacturing (Stratasys, 2015), as this technique is now suitable for fixtures with a demand for high tolerances and flexibility though still not for the size and load conditions of the lightweight gripper presented here.
- While it is valuable to integrate in fixture design more of the methods that have been developed within the engineering design methodology literature, lessons can also be learned from the fixture design literature as a specific case of engineering design methodology. One is that the notion of conceptual design could be extended to include investigation and design of the product features that present high uncertainties, for example layout and form design. The embodiment and detail design phases would focus more on routine design activities. Second, concept evaluation can be simulation intensive, which is rarely explicitly dealt with in conceptual design process models (Motte et al., 2014).
- The context in which CAFDSs operate need special attention. For example, in the reported industrial case, the CAFDS was intended to be used by production engineers during the whole product and process development process.

Author

Finally, using advanced materials is a challenge in an area where steel has been used for many different applications. This paper shows that it is possible, using KBE, to develop a CAFDS that automatically and efficiently generates dedicated fixtures.

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Paper VI

Integration of Computer Aided Design Analysis into the Engineering Design Process for use by Engineering Designers

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INTEGRATION OF COMPUTER AIDED DESIGN ANALYSIS INTO THE ENGINEERING DESIGN PROCESS FOR USE BY ENGINEERING DESIGNERS

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ABSTRACT

When developing products, engineering designers often face the problem that their candidate for a technical solution, ranging from a concept to a detailed design, needs to be analyzed by a design analyst before it is approved or rejected and the engineering designer can continue his/her activities within the product development process. If engineering designers have to send every solution candidate to a design analyst, a lot of time and money is lost. To avoid this, some Swedish companies have started to allow their engineering designers to use the analysis capabilities imbedded in modern CAD/CAE software.

In the literature on product development and on computer based design analysis (CBDA) both processes are fairly well described. However, this cannot be said about the interaction between the two processes. This is a growing issue as it represents core knowledge for developing efficient and effective integration concepts, which in turn can be developed into likewise efficient and effective approaches on how to assist the engineering designer to perform parts of the CBDA process on his/her own. Note that when we refer to CBDA here, this is confined to the use of FEM in the development of products, primarily based on working principles originating from the area of Mechanical Engineering.

Since we have been working on a process model for the integration between engineering design and design analysis, this has inspired us to utilize findings from these efforts to propose a conceptual model for a design analysis process driven by the engineering designer to be integrated into the product development process.

The proposed design analysis process model is based on the use of predefined *analysis methods* or *templates*. Templates are also utilized for QA (Quality Assurance) and monitoring of the analysis activities. Responsible for the development of the analysis methods and the templates are expert design analysts,

who develop these tools within a technology development process. Before allowing the engineering designers access to them, these tools need to be approved by relevant bodies within the industrial enterprise and/or by external sources such as those responsible for certification and risk management.

In this paper we present the development of the proposed integrated design analysis process model and an industrial case study, which incorporates a non-linear design analysis activity, utilizing the FEM-program Abaqus within the CAD-software Catia V5 and its imbedded optimization module.

INTRODUCTION

In most product development projects, computer based design analysis, CBDA, or simply design analysis for short, plays an important role for the establishment of the constitutive design parameters of the product-to-be. When we refer to CBDA/design analysis here, focus is put on the establishment of the structural, mainly the mechanical, properties of the product-to-be. This, in practice, restricts the scope of this paper to the utilization of FEM-based analysis tools. In the majority of product development projects, costs as well as increased effectiveness and efficiency are important factors for a successful outcome of the project. For example, by utilizing design analysis, the prototyping costs might decrease due to the need for fewer prototypes. If design analysis can be incorporated into the engineering designer's activities, it will substantially increase the possibility for the engineering designer to explore the available design solution space in a given project on his/her own and thus become more or less independent of a design analyst for quantitative evaluation of product concepts down to detailed design solutions.

During the development of a new concept or detailed design solution, there are usually a number of consultations between the engineering designer and the design analysts. After each of these consultations there is most frequently a need for an adjustment of the concept or the detail. A proposal for a change in the design is most frequently given by the design analyst to the engineering designer, who decides whether to implement the proposal or not or perhaps even create a new solution candidate which might result in additional consultations with the analyst. The number of consultations can be quite large for high-technological products. For example, at Haldex, a Swedish company specialized in brake products and brake components for heavy trucks, trailers and buses, the largest part of the disc brake, the caliper, can undergo 70-100 consultations between various departments, most of them between the design analysis department and the design department, see [1].

Since the responsibilities of the engineering designer and the design analyst are traditionally separated in industrial practice, the communication between the two is often a source of misunderstandings, delays and, even worse, of less robust and reliable designs. It is therefore important to improve communication and understanding by appropriately integrating the design analysis activities into the product development process. In order to facilitate this improvement in the integration of engineering design and design analysis, a proposal for allowing the engineering designer to take over parts of design analysis activities is presented here.

The development of new built-in features in current CAD/CAE software provides new opportunities for engineering designers; now these tools are no longer confined to the creation of the product geometry but also provide the means for design analysis, Knowledge Ware and design optimization.

As the engineering designer is traditionally responsible for generating the technical solution of the entire product and/or of parts of it, he/she has expert knowledge of the functionality of the product and its parts and of most of the external conditions and constraints which will be imposed on the product-to-be. Regardless of the engineering designer's expert knowledge, this does not mean that he/she has all the skills necessary to perform the design analysis on his/her own – even if we assume that the engineering designer has some insights into FEA (Finite Element Analysis). By providing analysis methods/templates for QA and monitoring of the design analysis activities, it is possible to allow the engineering designer to perform at least parts of the design analyses. Note that this implies that the design analyses are to some extent confined to "standardized" analyses, so non-standardized design analyses must remain the responsibility of a design analyst expert.

In this paper, we describe the development of the integrated design analysis procedure model as well as an application example project from industry.

POINT OF DEPARTURE

The proposed integration concept is supported by a number of Swedish companies who want to broaden their use of design analyses, thus planning for the integration of design analysis into the engineering design activity to be partly performed by engineering designers. One of the major obstacles in industry to design analysis performed by engineering designers, has been the QA aspect as well as the monitoring of the design analysis activities.

From a research project aiming at the development of an integrated engineering design and design analysis process model we have been inspired to initiate the development of the current design analysis process model. In preparation for this project, an extensive literature survey was carried out. The result obtained from this survey (covering engineering design, product development and CBDA literature sources) clearly showed the lack of an operationally oriented integration process model. Regardless of the access to such an integrated process model in the literature, industry is handling these issues on a daily basis. Therefore, another survey was done in a number of

Swedish manufacturing companies with in-house CBDA resources and consultants providing CBDA to industry. In this industry survey we found a number of companies using predefined analysis methods to secure the QA aspect as well as monitor the design analyses, and these findings have been our main source of inspiration and support for the proposed analysis concept.

In a recently finished project for a major Swedish truck company, it has been proven that the problems associated with QA and monitoring can be solved with the use of templates. These templates are developed in a separate process, a Technology Development process, by expert design analysts and verified and validated in an industrial setting, [2].

Finally, by utilizing some of the results obtained from the research project mentioned previously, it is possible to understand which factors are of importance for the integration of CBDA into the product development and thus for the engineering design process [3]. In Figure 1, the task clarification steps necessary for setting up a design analysis project are presented, see [4].

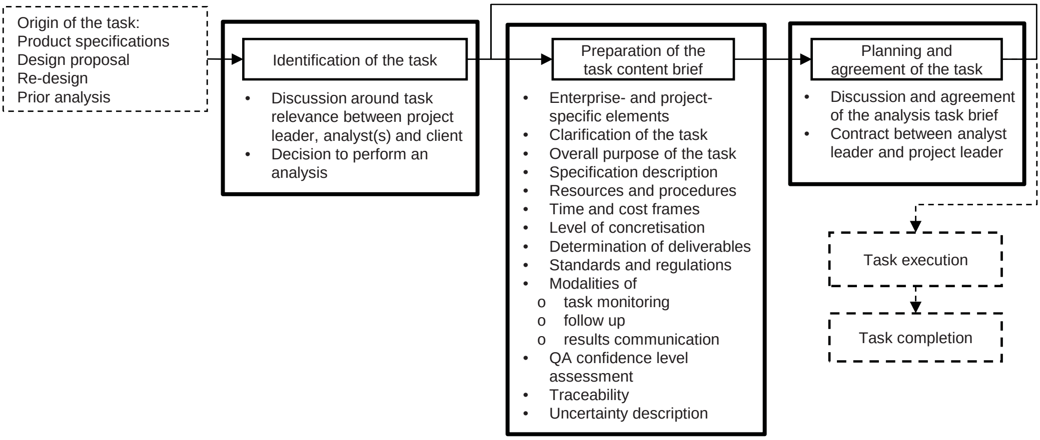


Figure 1. Analysis task clarification steps [4].

The analysis task clarification steps shows how information obtained from the engineering design process is utilized in an enhanced design analysis process model that implements several QA aspects such as QC (Quality Check), V&V (Verification & Validation) and uncertainties, allowing for a better integration of the design analysis activity in the overall engineering design process. Note that the design specifications need to be translated into analysis objectives useable as target values inside the CAD/CAE software, and measures for QA must be set [5].

In order to provide the theoretical foundation upon which the proposed design analysis process model is developed, the following "elements" should be elaborated upon: the engineering design process, the CBDA/design analysis process, process integration, development of the analysis methods/ templates and software integration.

The Engineering Design Process

Within the field of engineering design a large number of publications are available, ranging from research on engineering design processes, design methodology, and specific design methods and techniques to generic engineering design models describing the context in which the engineering design methodologies are to be used. In most of the literature on engineering design, the process is divided into different decision gates, phases, design activities and steps depending on the author, but also on country of origin, "design culture", in which the process is developed [6-9].

Figure 2 shows a simplified engineering design process model adapted to the level of concretization necessary for the understanding of design activities primarily involved in the integration issues between the engineering design and the design analysis activities.

The simplified process includes the following phases:

- **Specifications**: Assignment of measurable product specifications as a basis for the subsequent concept generation and concept evaluation.
- **Concept Design**: Generation of concept candidates and evaluation and selection of final concept.
- **Embodiment Design:** Establishment of product architecture and design of subsystems and major components.
- **Detailed Design:** Shape and form of individual parts and details including establishment of dimensions, selection of materials etc. A complete set of drawings are also to be included for the manufacturing of α prototype.
- **Verification &Testing**: The α prototype is tested with reference to the product specifications set out for the product-to-be.

Figure 2.The simplified product development process model.

The CBDA/Design Analysis Process

The design analysis process is generally described in the literature in terms of a number of steps to be taken in order to find a solution to the analysis problem. Numerous publications are available within the field and include research on fundamental design analysis methodology and recommendations on the use of specific purposes for generic design analysis process models, describing how the analysis methodologies are to be used. Previously, when analysis methods such as FEM were less widely diffused, the procedures describing their use in design analysis focused on solving the established numerical problem accurately and efficiently with a number of developed and outlined techniques and methods.

Such procedures can be found in works such as [10;11], to mention just a few within the area of design analysis. These procedures and methods became a very important part in the future development of the techniques. With the further development of software and simplified use of such analysis methods, process models have been eventually developed that include industrial aspects in order to support the practioner's actual design activities. NAFEMS (the National Agency for Finite Element Methods and Standards) in recent decades has proposed several process models that support the practitioner in his/her activities. In *How to plan an FEA*, [12], the workflow of design analysis tasks is extended to include steps that couple analysis to the design or development project.

In [13] the importance of establishing a clearly defined goal and of determining the level of uncertainty of the technical specifications is given special attention.

Other motives are the yields provided by decrease in time and resources, the possibility to introduce a coupled expert system, etc. In [2], a computer-based design system for lightweight grippers has been developed that can be used by production engineers with very limited knowledge of design and design analysis. The grippers are optimized through a simulated annealing algorithm and analyzed using FEM; the system is completely integrated into Catia V5®. In such cases, the synthesis and analysis activities are partly automated, and the "design work" is shifted towards the development of adequate software.

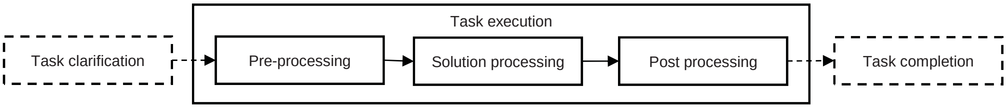


Figure 3. Overall design analysis process model taken from [4]

As a result of the research project on the integration between engineering design and design analysis mentioned previously, the complete design analysis process model is described briefly in Figure 3,[4]. This process model is utilized in the analysis model presented here. Each step includes important activities:

- **Task Clarification:** Agreement on the task, consisting of detailed planning of the analysis task.
- **Pre-Processing:** Preparing and setting up the computational model.
- **Solution processing:** Analysis execution.
- **Post-Processing:** Results verification and accuracy assessment.
- **Task completion:** Interpreting and evaluating the established results and hand it over to the project.

PROCESS INTEGRATION

Effective integration can be tackled in different ways. King et al. [14] have presented a framework (or 'good practice model') for the implementation of FEA and related computer-aided engineering (CAE) into the product development process. They state that effective integration is dependent upon 1) the organization of the product development process, 2) software, 3) hardware, 4) support structures for effective use of CAE in the product development process and 5) product data management.

The process models previously described fulfill these "criteria" and are thus accepted as the necessary constituent elements of the integrated analysis process to be presented here. As was mentioned earlier, it is important to emphasize once again the prerequisite that the engineering designers have none or limited knowledge of design analysis, which demands that all actions should be monitored and the quality of the actions taken be secured by the system. In order to accommodate these analysis methods/templates will provide the necessary means for accomplishing this.

Development of the analysis methods and templates

If we want to allow a non-expert, the engineering designer, to perform design analysis as described above, it is necessary to develop *analysis methods/templates* to support this activity. These methods/templates must be developed by expert design analysts and approved by the industrial enterprise and/or by external bodies such as those responsible for certification and risk management.

The actual analysis methods/templates should be in the form of straight-forward steps to be followed by the engineering designer, thus reducing the risk for mistakes and misunderstandings of the actual analysis procedure.

To be able to secure the QA and to make sure that the engineering designer only takes the steps he/she is allowed to take, templates are utilized for the monitoring of the analysis actions. These templates are developed by expert design analysts and, like the analysis methods, approved by the industrial enterprise and/or externally.

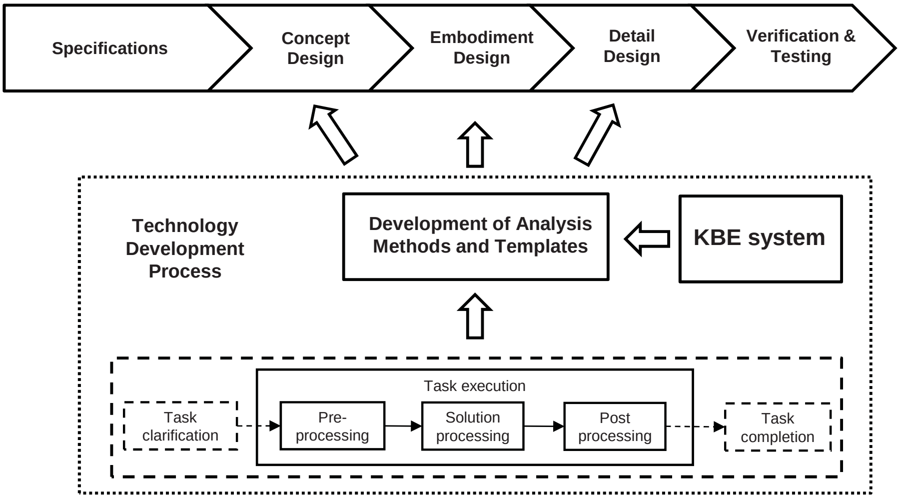


Figure 4. Schematic process model for the integrated design analysis process model.

The analysis methods/templates are all developed within a Technology Development process, which is carried out separately from the daily activities within engineering design and product development in the industrial enterprise.

The complete integrated design analysis process model is illustrated in Figure 4. Note that this model also includes a KBE system (Knowledge Based Engineering system). This is primarily used for capturing experiences from industrial practice in engineering design and analysis activities as well as monitoring and securing the quality of the activities performed. Furthermore, also note that information in the form of specifications (regarding both product and process) are utilized as input in this development activity.

SOFTWARE INTEGRATION

The actual integration is based on an integrated CAD/CAE-System; here the Dassault Systemes$^{©}$ Catia V5$^{©}$ has been used. Regarding the software integration issue, a number of authors have contributed to that area as well as have software developers. In [2;15] integrated CAD/CAE is employed for optimizing products by using design analysis and KBE. Using KBE is only one of many advantages that CAD/CAE integrated software offers. In [2] a design system is built with all the features available from inside the same software, in this case the Catia V5; [16] states that computer support should be *cooperative*, *subordinate*, *flexible* and *useful*. One of the problems when exporting geometry from CAD software to analysis software is that the connection to the original geometry is lost.

Another problem arises if there are errors in the exported geometry; the analysis expert must repair it within the analysis software. There can also be problems with the geometry, problems that the engineering designer did not think about when creating the geometry, for example small holes, small radius and other geometry that is not necessary for the analysis.

Making geometry that suits all kinds of usage demands high skill from the designer, but it is easy to solve. By using different configurations controlled by a parameter, the designer can activate and deactivate geometrical features simply by changing the value of a parameter. Other parameters can control dimensions of sketches and features and be used for optimization. After each of the consultations in the optimization process, the controlled parameter value is changed and the original geometry is automatically updated. Numerous publications have focused on this software integration at diverse levels: interoperability at feature level —CAD to CAE feature simplification and idealization [1;17], CAE to CAD reconstruction [18;19], new shape representation [20] at a higher-information-level [21;22] or complete integration in software packages such as PTC$^{®}$'s Creo$^{®}$ Parametric ANSYS$^{®}$ Workbench environment, Simulate$^{®}$, Dassault Systems$^{®}$' Catia$^{®}$ and Simulia$^{®}$ etc. The integrated design analysis process and its architecture are presented in Figure 5.

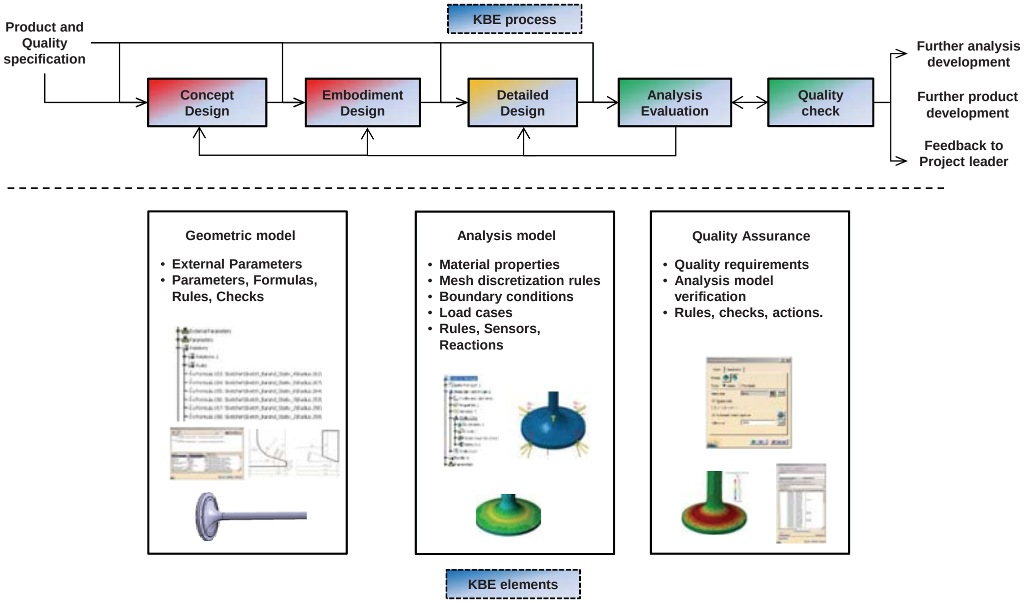


Figure 5. Integration of the process and its architecture(adapted from [2]).

INDUSTRIAL CASE

In this industrial project we set up two different goals. First, we wanted to verify and, if possible, to validate the design analysis concept. In this study, we especially focused on the development of templates and on studying how they were used as a link between product development and design analysis. A second goal was to find out if there are any differences between the FEM workbench GPS/GAS (imbedded in Catia V5), and Abaqus for Catia (a plug-in for Catia V5) in terms of capabilities and handling as well as in terms of integration with other Catia V5 workbenches, for example KBE and the Product Engineering Optimizer (PEO).

In this case, an exhaust valve and its seating for a truck engine have been used for the case study. Since it was decided to optimize the exhaust valve and its seating, the optimization and design analysis execution was expected to be rather time consuming. In addition to the execution itself, time spent for on the built-in features for QA and KBE also helps prolong the total analysis time. For these reasons a simple geometry, like the exhaust valve and its seating, was a perfect choice for the project. Note that in this case templates are utilized to accommodate a *fully automated* design analysis activity.

The project was carried out by five teams of senior engineering design students. These teams worked independently of each other under the supervision of an expert design analyst from the truck manufacturer and the supervisor at the university (the main author). In parallel to the project carried out by the students, a professional engineering designer and expert design analyst carried out the same project, but in the latter case in the "traditional" manner – consultations between the engineering design and the design analyst.

GEOMETRICAL MODEL

Building complex geometrical models and handling all the elements to be integrated, it is important to have an opened geometric model. All dimensions that are affected by the analysis or KBE have to be parameterized. Figures 6 show the first step in setting up the model, parameterizing and connecting it to the dimensions. The solids are parameterized, and the model is controlled and monitored by a set of formulas, checks and rules. A system of checks has been implemented to monitor the integrity of the geometry and dimension specification after changes. This also makes the design system more robust.

Using a Visual Basic script has enhanced user ability in this model. As this integration of design analysis is made by using templates, and as it is important to make sure that the user does not use values outside the allowed values; a dialog box is used as an input. Behind the dialog box, rules are checking the values, and if the values are not inside the accepted parameters, the rules can give a warning or refuse to accept incorrect values. Figure 7 is a picture of the user Visual Basic interface. In the dialog box the user can see all parameters and what dimension each parameter controls. Parameters for the optimization are also set in this dialog box. When all parameters are set; there are two buttons for applying the values to the model.

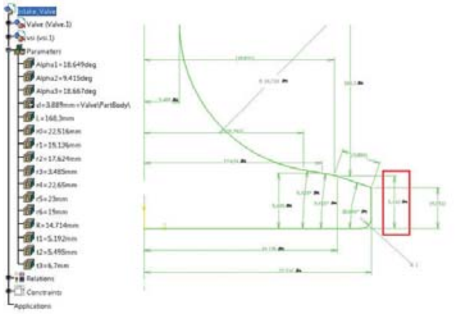


Figure 6. Parameterizing and connecting to the dimensions

In the model used for this project, the geometry of the valve (the contact between the valve and the seating) can change so that the pressure applied affects the model negatively. To be able to ensure that the pressure is always applied correctly, a rule was created checking so that when the dimensions are outside the allowed values the pressure is deactivated. This rule could only be used inside GPS/GAS as a contact connection inside AFC is not parameterized, and it is not possible to activate/deactivate this feature through a rule.

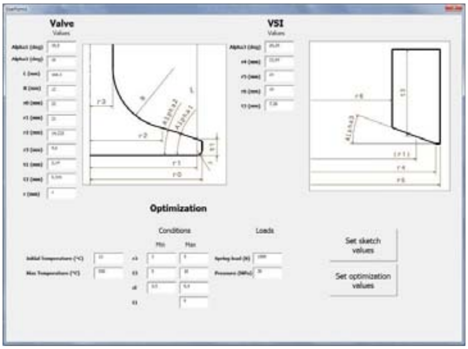


Figure 7. Visual Basic User Interface.

ANALYSIS MODEL

The analysis model contains information about the material properties, boundary conditions and load cases. It also contains mesh discretization rules [17]. For the optimization step, coarse mesh is used: element size 4 mm, 1st order (linear) element, and geometric representation within 0.2 mm. For an improved geometric representation, 2nd order (parabolic) element is used. Depending on the order and quality of the elements, different amounts of time are required to solve the problem.

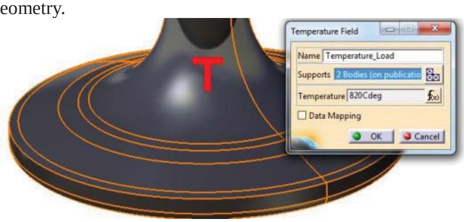
Quality assurance

Finally, a quality check and verification of the final results is performed. The quality check consists in a mesh convergence study, element quality control, and reaction force summary, together with the assessment of the design system assumptions. Once this final analysis is performed, the results are handed over to an analyst for final assessment of the confidence in the performed analyses and established results.

Geometric model instantiation

The geometric model instantiation is the first step of the part's geometrical design and aims at generating a first geometry.

The values from the user input interface are assigned to the geometric model, and the model is automatically updated; the KBE checks that all dimensions are within the allowed values. As all dimensions are set and the geometrical model is up to date, the engineering designer does not have to manipulate the geometry.



Temperature Field

Name: Temperature_Load

Supports: 2 Bodies (on publicatio

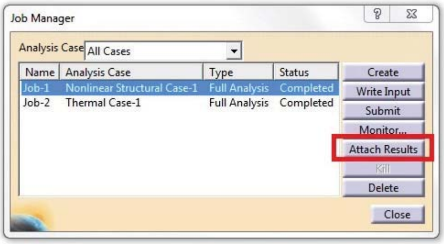
Temperature: 820Cdeg

☐ Data Mapping

Figure 8. Thermal condition applied to the model.

Analysis model instantiation

An analysis model is then built up with solid element mesh on each part with assigned physical properties. Contact connection is created and a friction coefficient is assigned for the specific material of the models. We also have to set up parameters for the thermal analysis; see Figure 8.



Job Manager

Analysis Case: All Cases

Name	Analysis Case	Type	Status
Job-1	Nonlinear Structural Case-1	Full Analysis	Completed
Job-2	Thermal Case-1	Full Analysis	Completed

Figure 9. Thermal result attatchment.

There is a difference in when to apply this in AFC and GAS/GPS. Setting up the environment is no major difference, but in AFC the thermal analysis must be made before the static analysis; see Figure 9. When the results from the thermal analysis are available, we start the static analysis and add the previous results from the thermal analysis. A first calculation of the model is performed with the objective of applying all the required input to the subsequent optimization.

After solving the model, the stress and deformation results needed for the optimization are automatically available through the sensors. The user does not need to carry out any action for this step regarding the evaluation of the model.

Optimization

Once a first analysis model is instantiated, the optimization features are introduced. These elements consist of free parameters, constraints and target values. The free parameters are those that the optimization system can change. In our problem, these are the cross sections, thicknesses and diameters of the beam elements of the gripper base. The constraints are those given by the specification and by the material mechanical properties. The target value (optimization function) is to minimize the stresses. During this optimization process it is possible to monitor the progress and to interrupt it. After the completion of the optimization, all calculated values are available in a spreadsheet.

The optimization algorithm used in the PEO of Knowledge Ware is a simulated annealing algorithm whose details are described in [23]. The algorithm parameters (such as stress) are controlled by Catia V5. Between 30 and 90 iterations are usually needed to optimize the model, which amounts to about 2 to 12 hours of solving time.

Result

In this project, design analysis was integrated into the engineering design process. Five different groups of students have, independently of each other, successfully implemented templates and KBE and performed the design analyses. From the outcome of this case, it is clear that the use of templates and implementation of selected design parameters, target values and the setup of the design optimization was suitable for the proposed design analysis concept. The integration works well and the engineer evaluates concepts faster. The work is less time–consuming, and misunderstandings or loss of information are avoided as the engineer performs the design analysis on his/her own. As the integrated developed technology governs the process with the help of the KBE, it is not possible for the designer to set values or for the software to produce results outside these limitations. By implementing Visual Basic (see Figure 7) the potential to make mistakes or to enter the wrong value has been further reduced.

DISCUSSION AND CONCLUSION

In this project, design analysis has been integrated into the engineering design process. This integration has both advantages and disadvantages. A summary of these is listed below:

- Since it is the designer who performs both design and analysis, the work can be carried out directly when needed, eliminating any deficiencies or misconceptions in the exchange of information that might occur when an analysis performance is handed over from the designer to the design analyst.

- The designer can perform evaluations of a concept or a detail early on in a design phase and thus be able to eliminate a large number of candidates without the involvement of the analysis department; the work can be focused on the concepts/details that are better suited for the design solutions.
- The lead time for developing new products can be significantly shortened as the designer can perform design analysis directly when needed instead of having the work sent to the analysis department to be completed when they have the time [24].
- Designers' knowledge of analysis may be limited, which means that clear instructions / procedures on how the tool is to be used must be developed.
- The designer may, in some cases, need the assistance of an expert design analyst when analyses are carried out, when interpreting the results and when unexpected difficulties occur during the analysis.
- The introduction of analysis methods/templates, supported by KBE and developed by design experts or design analysts during a Technology Development process has proven to be a successful concept for facilitating design analysis performed by non-expert design analysts.
- The extensive use of templates makes it possible to monitor and secure the quality of the design analysis project.

The integration of the engineering design and design analysis activities has been both tested and validated in 3 different projects, that is, 2 other projects beside the one reported here. In [2], a computer based design system for lightweight grippers has been developed that can be used by production engineers with very limited knowledge of design and analysis. Finally in [25] a CBDA system had been developed supporting the design and analysis of a bracket for the intercooler system in a truck engine. In this project the validation of the optimization has been carried out together with the company's analysis experts utilizing an external software denoted Inspire [25].

The result from the industrial case also shows that, even though both GPS/GAS and AFC (Abacus for Catia) are imbedded in the Catia V5 environment, there are advantages and disadvantages associated with the use of both softwares.

- GPS/GAS is a FEM program confined to linear analysis and also limited regarding analysis of contact problems and advanced analysis.
- AFC has technology from Abaqus© and has the advantage of its capability of non-linear analysis both in contact (more options) and multi-physic analysis, and is preferred in advanced analyses.
- Comparing the analysis result from GPS/GAS and AFC it was concluded, when analyzing contact with small deformation and thermal, there was no significant difference.
- GPS/GAS has been part of Catia V5 from the beginning and is more integrated in the V5 environment than AFC, which appeared when functions within KBE and PEO were to be used.

In conclusion, both softwares are powerful and easy to use, and it is important that the user have basic knowledge of design analysis. Furthermore, by integrating analysis into the engineering design process and by using GPS/GAS or AFC, all activities are made on the same CAD model, no geometrical or parametric information is lost and all changes are updated to the CAD model directly. The proposed design analysis concept has so many advantages that the truck company immediately after having finished the industrial project accounted for above, decided to proceed in adopting this concept for all of their engineering designers. This implementation project has already started and the actual implementation is planned for late 2013.

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Paper VII

Using Templates to Support the Engineering Designer Performing Computer-Based Design Analysis

VII

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ABSTRACT

In their quest for a more efficient and effective utilization of the resources allocated to engineering design projects, and thus to the overall product development project from which the current design task(s) originate, an increasing number of companies allow engineering designers to perform Computer-Based Design Analysis (CBDA) on their own – CBDA is here confined to quantitative analyses using finite element-based structural and thermal analyses, Computational Fluid Dynamics, and Multi-Body Systems. Since all of these tools require a certain level of expertise in order to be successfully utilized in industrial practice, the types of analyses performed by the engineering designers are confined to simple, straightforward ones.

In striving for an increase of the individual engineering designer's possibilities to actively participate in CBDA in industrial practice, an online survey has been carried out and reported in [1]. The main objective set out for this survey was to give an overview of the current situation in the global industry regarding CBDA tasks being performed by engineering designers, what positive effects they might present to the industry and how they should be implemented for best result. Resulting from this survey, one new type of support, Template-Based Design Analysis (TBDA), was singled out as very promising for future development. TBDA is a support to be used in engineering design analyses based on the utilization of the advanced features provided by high-end Computer Aided Design (CAD)/Computer Aided Engineering (CAE) software in supporting and guiding as well as monitoring the design analysis performed by the engineering designer.

Since TBDA is still in its infancy, substantial development needs to be invested in it to make it the full-blown support needed in industrial practice. To be able to contribute to the development of TBDA, it is essential to acquire knowledge about how companies, both national and international, are planning to introduce and utilize TBDA in industrial practice. It is likewise of importance to acquire knowledge of the arguments against an introduction of TBDA.

To that end a new online survey has been carried out, focusing on the introduction and benefits as well as the disadvantages associated with an implementation of TBDA. The survey was sent to 64 recipients, 41 of whom were selected from the previous survey [1] and 23 came from Swedish companies known to the authors to utilize CBDA on a regular basis. The limitation to Swedish companies was due to practical as well as economic reasons, as these companies were also invited to participate in interviews. The main objective set out for these interviews was to get an in-depth view on the outcome of allowing engineering designers performing CBDA/TBDA in industrial practice. An additional objective was to get an indication as to the validity of the responses obtained in the online survey by comparing the

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results from the interviews with the responses given by the companies to the survey

42 of the 64 recipients, from 17 countries, completed the survey. All of the invited Swedish companies completed the survey. However, due to the risks associated with revealing proprietary information during the interviews, only 5 out of the 23 companies were willing to participate in the interviews.

The introduction of TBDA in an industrial setting has resulted in many advantages, such as shorter lead times, opportunities to generate more concept candidates, and increased collaboration between the engineering designers and the design analysts, all of them contributing to more mature technical solutions. Three different automation levels of TBDA have also been identified and accounted for as well as exemplified. In the companies in which TBDA has not been implemented, some of the reasons for not doing so are high costs, company policy, and the lack of knowledge and experience on the part of the engineering designer. This paper presents the results from both the new online survey and from the interviews.

INTRODUCTION

The responsibility for all quantitative Computer-Based Design Analysis (CBDA) performed within the engineering design process, rests traditionally with the engineering design analysis experts, here the design analysts. In the majority of companies, the design analysts are working within a specialized engineering design analysis department. CBDA is the comprehensive term for all quantitative computer-based design analysis activities within engineering design, or simply design, here confined to the utilization of Computer Aided Engineering (CAE) tools such as the Finite Element Method (FEM), Computational Fluid Dynamics (CFD), Multi Body Systems (MBS), and supportive tools such as Knowledge-Based Systems (KBS) and optimization methods/software (shape, topology and others), all within mechanical engineering.

However, there have been recurring efforts towards allowing the engineering designer to perform CBDA. This approach has yielded mixed experiences in the past, but nowadays between 30% and 40% of the companies allows their engineering designers to utilize design analysis tools on a regular basis [1;2]. Introducing design analysis to the engineering designers has often proved to be very effective [3]. This is especially relevant now that 30% of all analyses are performed during the conceptual design phase [4]. To that end, several types of support are available: usage of guidelines, supervision by a design analyst, special training etc.

In a previous online survey [1], the main objective was to give an overview of the current situation in industry regarding CBDA tasks being performed by engineering designers, what positive effects it might present to the industry and how it should be implemented for best result. This has been done by means of a survey addressed to members of engineering associations such as the National Agency for Finite Element Methods and Standards (NAFEMS) and the American Society of Mechanical Engineers (ASME), as well as targeted companies. The main subjects touched upon by the survey are the proportion of companies applying this approach, the type of support used by the engineering designers, the degree of freedom they have, and the challenges associated with this approach. Resulting from this survey, Template-Based Design Analysis (TBDA) was identified as a very promising support for an extended use of CBDA in industrial practice.

TBDA is defined as a pre-developed code that supports or guides those performing design analysis tasks, e.g. from predefined settings available in traditional CAE tools to scripts developed in-house and advanced usage of KBS. TBDA can be used to allow engineering designers to perform certain specific types of analyses while leaving the most advanced analyses to the design analysts.

Generic templates have been used for many years by design analysts, and the normal usage for templates is a form of basic template used e.g. for creating geometry for defining different types of predefined coordinate systems, functionality and license limitations. Ansys, in its latest releases, has introduced a new aid that is described as templates [6]: modules needed for a specific type of analysis can be chosen from different sub-templates to build up an analysis template. In a case study within Ford Motor Company's North America Engine Engineering Organization, an analysis template to accelerate the initial geometry and analysis generation process has been developed [7], focusing on simplifying and automating task-related analysis connections, boundary conditions and mesh generation. Both in Ansys and in the case from Ford Motor Company, the main focus was on the analysis performed by a design analyst.

The development and use of TBDA for engineering designers is challenging. Engineering designers have generally limited skills in analysis compared to design analysts. Templates for engineering designers might have to be more focused on product type and/or one type of analysis. However, the potential benefits are numerous. The engineering designer can, for example, perform preliminary analyses before sending the design to the design analyst for additional analysis. It allows him/her to develop and simulate more concepts, even "exotic" ones, and also the engineering designer can perform the analyses of new concepts that in some companies have very low priority [8]. The engineering designer can perform analyses on his/her own instead of asking for support, thus freeing resources for more demanding analysis tasks. The templates can be designed so that they ensure the quality of the design analysis process and its results, which is important in a Quality Assurance (QA) perspective.

What is the current position of the industry in this matter? There are very limited insights into and knowledge of the use of templates for engineering designers in industry. Several industrial surveys investigate CBDA performed by engineering designers, e.g. [2;9;10], but TBDA is not touched upon. There is no knowledge of the spreading of TBDA or of the attitude of the industry towards the use of templates in industry. The goal of this paper is to bridge this knowledge gap. In order to remedy the lack of information regarding the use of TBDA by engineering designers, an international survey and a number of interviews have been carried out.

The results from the international survey and the interviews reported in this paper touch upon 1) the implementation of TBDA relative to the engineering designers' alternative CBDA supports used in industry such as guidelines, training, etc.; 2) the usage of TBDA: the different types of templates used (from basic to fully automated), the types of analysis performed by using templates, exemplified with industry cases, the implementation of TBDA into the product development and engineering design processes; 3) issues related to the development and implementation of templates, and the knowledge and training required of the engineering designers; 4) impact of the use of TBDA for engineering designers on development projects, challenges and future developments of TBDA. In the remainder of this paper, the term templates and TBDA are confined to the design analyses performed by the engineering designer, not to those by the design analyst.

METHODOLOGICAL APPROACH

This investigation is composed of an online survey combined with a set of interviews. The online survey made it possible to reach a large number of professionals; especially those active on the global arena, and to get quantitative data from closed questions. The interviews were conducted to get in-depth answers on open questions related to the outcome of allowing engineering designers performing CBDA/TBDA in industrial practice, such as descriptions of templates implemented, related issues, challenges and recommendations.

Survey

The format of the survey was an online survey, in order to be able to reach respondents internationally. The online survey tool www.quicksearch.se was used. The structure of the new survey is shown in Figure 1. After some background information and some questions about the company's CBDA process and its integration with the engineering design process, respondents were asked whether the company authorized the engineering designers to perform CBDA. If so, several questions were asked regarding the kinds of support the company provided to the engineering designers (guidelines, training, templates, etc.). Finally, some questions were directed to the companies not allowing the use of CBDA in general by engineering designers. The new survey contains a maximum of 34 questions. Beside closed questions, there were opportunities for respondents to give comments and supplementary information.

The recruitment of respondents to the previous survey [1] consisted of an open invitation to members of the NAFEMS and Design Society organizations, different member groups within ASME and LinkedIn, and from a set of selected companies known to utilize CBDA. A total of 77 respondents answered the previous survey [1]. 43 of these were willing to answer additional questions, but only 41 left a valid e-mail address. 19 of the 41 completed the new survey. 23 additional recipients, from Swedish companies known to the authors to utilize CBDA on a regular basis, were invited to participate in the interviews. All of these completed the survey. Thus, the total number of respondents who answered the new survey was 42. The survey was open for two months, February to March, 2015.

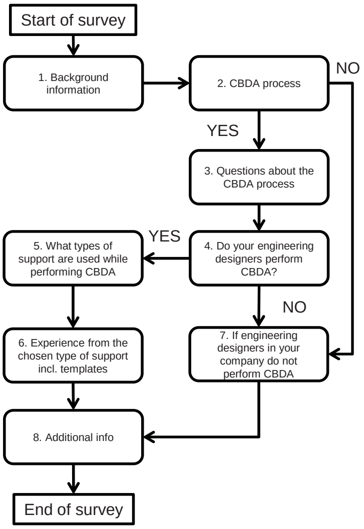

Figure 1. Main structure of the new survey

Interviews – general approach

There were several motives behind the choice of interview technique. Some questions related to TBDA required extensive description and direct interaction for immediate feedback (for example, description of a developed template). Many questions led to confidential information being disclosed in order to allow for a better understanding of the answers. The interviewee could sometimes show some specific documents (design analysis procedures) or ask co-workers for specific information.

Few companies use templates for engineering designers, and the results from the interviews have to be interpreted qualitatively. Each of the companies interviewed gives an account of how they use templates and the impact it has on product development. Nevertheless, these cases can be used to give a picture of the use of TBDA for engineering designers in industry. A similar approach (with 5 interviewed companies) has been reported in [11] to develop a model for the organization, structure and support of design analysis in companies. It can also serve as a basis for reflection both for companies and researchers, e.g. on whether TBDA for engineering designers is an interesting kind of support or not.

The companies accepting to participate in the interviews were sent the complete set of interview questions in advance. An interview lasted for about 1½-2 hours. All interviews were recorded and the notes taken during the interviews were later compared with the recorded interview. The last step was to send the results compiled to the respondents for validation. This approach, based on a combination of a questionnaire and an interview, has already proved successful in the past (see [2;12;13] where a full description of the interview technique is provided). The organization of the reporting of the interview process and results has been based as much as possible on the recommendations of [14] and with reference to [15] and [11].

Topics of the interview

The following topics were included in the interviews. First some questions of general character were asked regarding the company, its personnel and its products together with a focus on the integration of the engineering design process and the design analysis process. The second set of questions was oriented towards the extent of the usage of TBDA and the automation level used within the company. The third set of questions dealt with how and when TBDA should be used and the implementation of TBDA in the company. The fourth set of questions dealt with education/training, documentation and traceability of analyses performed. The fifth set of questions finally, concerned the impact of TBDA on the business, on the development process and on the products developed. The companies were also asked about future plans for TBDA.

Selection of companies for the interviews

As many interview questions were sensitive in nature, and as the interviewee was highly ranked in the hierarchy (head of development or simulation departments), only companies with which the authors had had collaboration and/or which were known to perform CBDA on a regular basis were contacted. Of those contacts, 23 companies were of interest. In 7 of them, engineering designers performed TBDA. In the end, only 5 of them accepted to be interviewed due to the risks of revealing proprietary information previously mentioned; a small number of respondents but significant for the purpose – compare with the investigation reported in [11].

The 7 international respondents from the new survey, who had answered that they use TBDA at different automation levels, were also tentatively approached, but none of them were willing to participate in an interview.

PROFILE OF THE COMPANIES AND RESPONDENTS

The profile of the companies and respondents who participated in the new survey and interviews are detailed below. Note that the figures from the new survey include data obtained directly from the interview participants. Furthermore, note that Figure 2 to Figure 5 include two diagrams. The first diagram represents the profile of all companies and respondents who answered the survey. The second represents the profile of companies and respondents who have implemented TBDA for their engineering designers.

Survey results

One third of the respondents were managers and one third engineering designers, see Figure 2, left. Most of them hold a Master's degree (Figure 3).

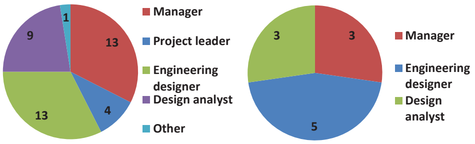

Figure 2. Primary position of the respondent

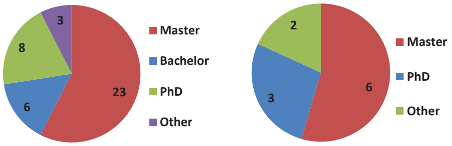

Figure 3. Formal level of education of the respondent

The companies, classified in industrial branches according to [16], are mainly operating within transportation (31%), aerospace and defense (13%), energy (13%) and industrial equipment (11%), see Figure 4, top.

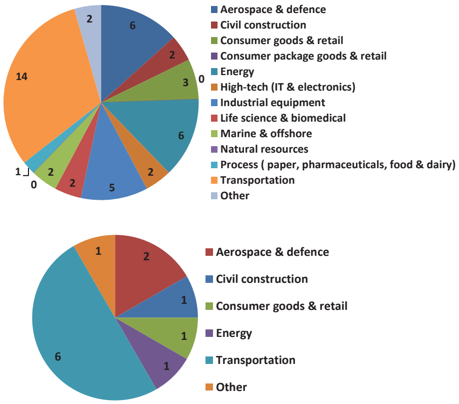

Figure 4. Companies' distribution across industries

The companies which have implemented TBDA are mostly in the automotive industry (Figure 4, bottom). The companies have also been classified according to what they primarily offer: technical systems, complex components (suppliers) or engineering consultancy, as this implies different development activities. A majority of respondents (53%) come from companies developing full technical systems, and 28% are engineering consulting companies (Figure 5, left). Not surprisingly, much fewer consulting companies have implemented TBDA (Figure 5, right).

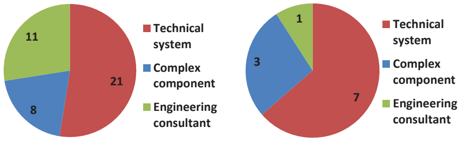

Figure 5. Companies' main activity

Of the 42 companies that answered the survey, 28 (67%) answered that they allow their engineering designers to perform CBDA. Companies that have answered our survey are mostly large companies (>100 engineering designers) followed by small companies (1-10 engineering designers) and midrange companies (11-100 engineering designers). Interestingly, when it comes to the companies that have implemented TBDA, small companies are followed by large and midrange companies, see Figure 6. This indicates that the implementation of TBDA is influenced by the number of engineering designers. In small companies it is expected that the engineering designer handles most, if not all, of the issues associated with his/her role as engineering designer. The need for engineering designers able to perform CBDA on their own is thus more articulated in these companies. In larger companies, the pursuit of increased efficiency is highly prioritized, resulting in the need for engineering designers to take over parts of the design analysis activities. Figure 7 presents the number of design analysts in the responding companies that allow their engineering designers to perform CBDA or TBDA.

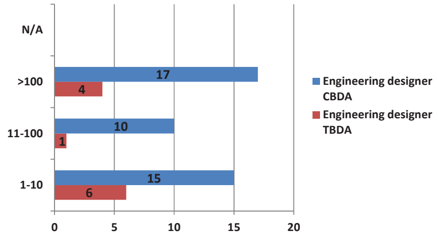

Figure 6. Number of engineering designers in the companies allowing them to perform CBDA/TBDA

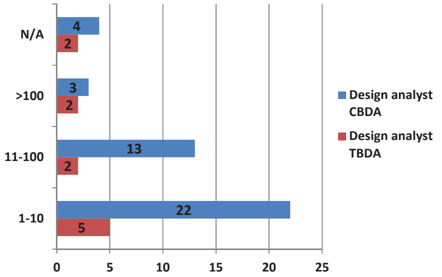

Figure 7. Number of design analysts in the companies allowing their designers to perform CBDA /TBDA

The software used for CBDA is Catia V5, Autodesk and SolidWorks followed by Pro/E, NX, and other. For those who have implemented TBDA, the pattern is almost the same, Catia V5, Autodesk, SolidWorks and Pro/E, see Figure 8. To be able to implement knowledge that is needed for implementing TBDA, integrated solutions are needed, which constrains the companies' choices.

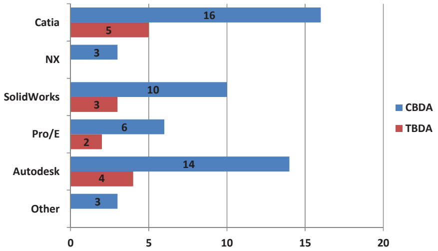

Figure 8. CAD software used in the companies allowing their designers to perform CBDA /TBDA

Interviews

The different companies interviewed have the following profiles (presented in the same fashion as [11]).

One company is a heavy truck manufacturer. The transportation of goods on heavy trucks along our roads has changed radically over the last 10 years. From previously focusing on reliability and comfort, it has now received a great deal of attention from an environmental point of view. This means that the majority of vehicle components must now be optimized with respect to weight. CAE is important as many different types of simulations are needed. Two of those are optimization and FEM, which have to be used to a greater extent than before. For this to be feasible, the designer's role has become even more important. Within the company there are a number of different departments, all of them with their own design analysis departments which are responsible for all simulations within the department. During the last few years the designers have also been trained to carry out design analysis. There are still important processes around the CAE simulation that have not yet been adopted. Storage of resulting data is one of those. Through the integration of the engineering design and analysis processes, important preparations for the implementation of TBDA have already been started.

A second company manufactures production equipment for food packaging. In recent years, competition has increased and the company is now beginning to explore some different types of options. How to reduce development costs and the cost of the product but at the same time double the capacity of the manufactured product, are two future goals they are looking into. In recent years, their engineering designers have started to use different types of simulation tools. Their engineering designer simulates different design solution candidates by using different tools, for example linear and non-linear analysis, MBS and tolerance analysis. Within the company, there are several computational departments that perform more advanced analyses but also provide support to designers in their simulation work.

The automotive industry, in which the third company operates, faces the same challenges as the heavy truck industry. Demands for less environmental impact and other new regulations also force them to use recycled plastic materials. New lightweight materials or different combinations of them (hybrids) are some of the challenges they are facing. At the same time high quality is important; comfort has to be improved. By introducing design analysis for their engineering designers, they are able to increase the number of simulations performed, which is needed if those new challenges are to be met. The main focus for their engineering designers is to perform linear analysis both at system and part level. If that is to be accomplished, some new type of support for the engineering designers will be needed. TBDA is one of the tools that are being evaluated. The design analysis is organized with a large group of design analysts responsible for all simulation in the company. The latest change made was to locate a few design analysts in the same office as the engineering designers for support and collaboration.

The fourth company is a multinational company that develops, manufactures and distributes products for brake systems on heavy commercial vehicles. The customers are typically manufacturers of heavy trucks, buses and trailers. The design analysis department has a main group that is responsible for all analyses, and there are smaller groups in different departments working in closer contact with the engineering designers. The implementation of TBDA today is still in its first stage. They are planning for a full implementation of TBDA at all of their sites worldwide and for all of their products.

The fifth company is in the defense industry. Most of the products that they manufacture are one-off. Their design analysis department performs most of the analysis work within the company, but the engineering designers are allowed to perform design analysis for the exploration and evaluation of concept candidates. They are only allowed to use linear analysis, though. The company now focuses on implementing a new standard for all engineering designers, and when all processes are updated, there are thoughts of implementing some variant of TBDA.

FORMS OF CBDA SUPPORT FOR ENGINEERING DESIGNERS

Most companies from the survey give their engineering designers some kind of support (only one company allows their designers to perform design analysis without support). Figure **9** represents the use of different types of support along the development lifecycle of a product. The total number of companies using each type of support is also indicated (one company might use one type of support in several development phases). The use of guidelines and supervision by a design analyst are the types of support used most often. All types of support are used in concept and detailed phases. Analyses are less often performed in embodiment design, which can be explained by the fact that design analyses are less needed for the design of the product layout and architecture. Engineering designers are probably less often called on for design analysis during production preparation (advanced analyses for testing and validation) and post-production (analysis of defective products, for example). Other types of support reported are: continuous training during projects (3 companies), collaboration with academic institutions or software vendors (2), experts available for questions (2)—this could be similar to supervision by an analyst—or non-disclosed information. 14 companies in total use templates (7 international respondents and 7 domestic companies). That is the least used form of support.

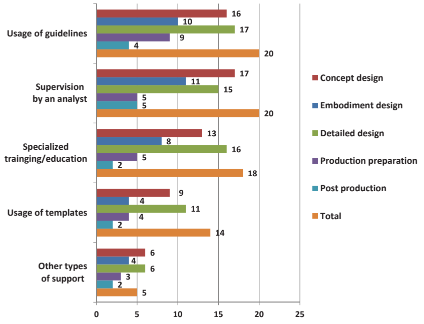

Figure 9. Types of support used during different product development phases

Supervision by an analyst normally refers to an internal source (all the companies using this support) or a senior analyst (55% of the companies). In 30% of the companies an engineering designer is used for supervision. One company has a resource employed 100% for this task, see Figure 10. When using guidelines, 90% answered that guidelines are available to the user in electronic form, 25% in paper form.

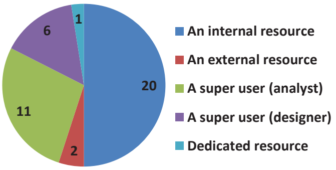

Figure 10. Resources called on for supervision

The resource used for the development of these types of support is reported in Figure 11. The results indicate that this is distributed equally between engineering design and design analysis departments, but when special training or education is needed, external resources (engineering consulting company, academic institution, other) are often hired for this.

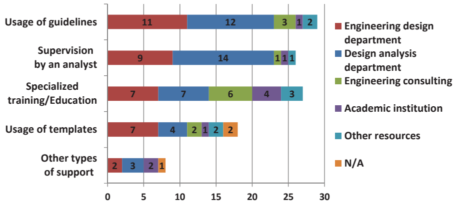

Figure 11. Resources called on for the development of the different types of support

Finally, the respondents were asked how the company and the users value these forms of support (on a 1-5 scale). Note that these ratings are the respondents' appreciation of how highly the company and users value the support. This may not reflect the actual appreciation of the company and users but gives a strong indication of these values. When implementing these different types of support, it is indeed important to find out which type of support has been of most value both for the companies as a whole and for the users. The answers are shown in Figure 12 and Figure 13. These types of support are relatively well accepted by the companies (3.8 in average). The forms of support most appreciated by the companies are the use of other types of support (4.3), supervision by an analyst (4.0), special training (3.8) and guidelines (3.6). The use of templates gets an average of 3.1.

The answers show that the users value all types of support less highly than the company (3.5 on average). This could be an indication that they are not pleased with the fact that they have had some limitations imposed upon them or that they feel supervised, see Figure 13. The average value for other types of support is 4.2, supervision by an analyst 3.9, special training 3.3, guidelines 3.1, and templates 2.8.

By comparing Figure 12 and Figure 13, we find that the templates were less highly valued by the engineering designer. One explanation, according to the companies interviewed, is that the engineering designers have been trained in basic design analysis to be able to use the analysis software. They have therefore little interest in starting working with TBDA, which constrains their freedom in their analysis work. Another reason is that their workload is too high.

In both cases the use of templates gets the lowest score. This can be explained by the fact that it is a less proven type of support. The companies interviewed were very positive towards TBDA, and no other explanation could be found.

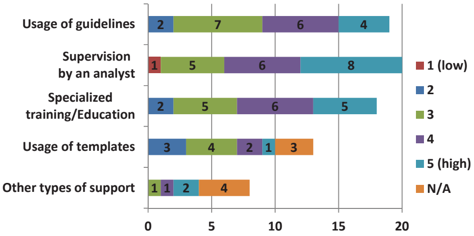

Figure 12. Company's assessment of the value of the different forms of support

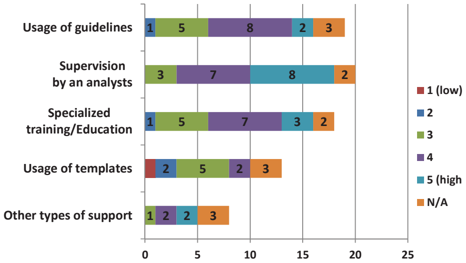

Figure 13. Users' assessment of the value of the different forms of support

USE OF TBDA

A preliminary finding is that the companies interviewed stated that they are in the early stages of their implemention of TBDA. Many of their TBDA projects served to test whether templates helped engineering designers perform design analysis and increase the product quality. It should be noted that most of these projects were performed for real products or parts, and their solutions have been implemented.

In this section, the use of TBDA in industry is described. This covers 1) the different forms of templates used, which can basically be classified according to how much they automate the design analysis task; 2) the types of analysis performed (FEM analysis, CFD analysis, etc.); 3) the position of TBDA in the overall development process of the companies.

Different forms of automation level of TBDA

Templates can be categorized in three different types: basic level, semi-automated level and fully automated level.

In the following sections, these three automation levels are described and exemplified with cases derived from the companies interviewed.

Basic level

At the basic level, the engineering designer has a large amount of freedom to perform design analysis, but some features of the CAE software are locked, in order to ensure a certain quality to the result. Pre-processing activities can be constrained: meshing possibilities may be limited, the number of nodes may be reduced, or the engineering designer may not be able to perform non-linear analysis. Some pre-defined settings might be added, such as warnings when some values are attained. Finally, some equations and rules can be added, such as automatic calculation of weight. The engineering designer, on the other hand, is quite free to work with the geometry of the product, the determination of the load cases etc. The template is always supplied with a set of guidelines explaining the different steps to take to make a correct analysis.

In one of the companies, such a template has been developed for the design and analysis of engine brackets (for more information, see [17]). Many different brackets were not properly analyzed in the past. Safety coefficients were applied instead. The company had decided to improve the development of these brackets with the goals of decreasing weight and cost, which would require a finer analysis of the structural properties of the different brackets. Moreover, the company wanted to leave this task to engineering designers entirely so as not to iterate with an overloaded analysis department. Other demands were that it should be possible to choose a different material, it should be easy to use and guarantee QA aspects, and the product should be fully developed when the engineering designer handed it over for manufacturing. To that end a template was developed.

The template was developed within Catia V5, using the integrated CAD, Finite Element (FE) and KBS capabilities of the software. Predefined settings developed in this template were, for example, the tolerance and order of the elements and a warning when the stress limit reaches the limit for the chosen material. Knowledge Based Engineering (KBE) features connected to the geometrical model are illustrated in Figure 14. A special method, in the form of guidelines, to be used in combination with the basic level approach, was also developed.

The outcome of the project was a weight reduction by 80%. In Figure 15, a newly developed sheet metal bracket is presented, which was developed during 2 months' time. According to the company, this type of development would not have been possible due to the long lead time between each iteration the engineering and analysis departments.

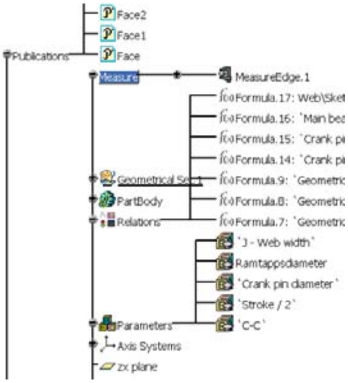

Figure 14. KBE features for TBDA

As this was a pilot project, a design analyst supervised the users when performing TBDA. The project resulted in the development of new guidelines. Templates have not yet been implemented in the daily work, the intention from the management being that, when all support processes have been brought up to date, TBDA is going to be used by the engineering designers or other personnel in the role of design analysts.

Figure 15. New sheet metal bracket developed with the help of a basic level template

Semi-automated level

In the semi-automated approach, the template interacts with the user, controlling and monitoring part of the process. One case is described below.

A semi-automated level template was developed for the design of a crankshaft and its variants. The crankshaft is the first part of the engine that has to be designed, as the rest of the engine depends on its design and function. A new crankshaft needs to be designed for each new version of the combustion engine, depending on the demands for this new vehicle. A semi-automated level of TBDA was developed for the analysis and optimization of the crankshaft.

The first part of the template dealt with the parameterized transfer of any new design of a crankshaft in the analysis template. The exchange of one crankshaft design for another for each analysis was simplified and secured.

After that, the geometrical instantiation is made, and the semi-automated design analysis can be started. The analysis template (pre- and post-processing) is generated with special settings. The first step is to load a design table with predefined values for the analysis from an Excel table; it is the form of min and max values and the user applied appropriate values for the specific analysis that is to be performed. The predefined values come from the design analysis department, and the values depend on what type of crankshaft is to be optimized. The next step is to adjust the settings for the Design Of Experiments (DOE) optimization, and when this is done the optimization starts. At the same time, a new design table is created where all the results from the optimization are stored. When the optimization has ended, there are around 5-6,000 results to be evaluated. When the results need to be visualized, the engineering designer chooses a suitable configuration among the results, and the calculated result is displayed. In Figure 16, one of these results is shown. The result is evaluated by a small group including the engineering designers, a design analyst and the person responsible for physical testing.

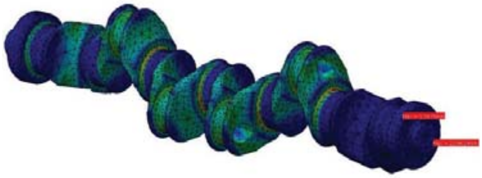

Figure 16. Result of DOE optimization

The company's feedback on this template is that it is very useful, and the knowledge of the product gained has been important. The crankshaft design obtained with the help of TBDA is used for the final product.

Fully automated level

At the fully automated level, the engineering designer has no control over the analysis part. The engineering designer prepares a geometry based on specific constraints, submits it and receives a completely analyzed and optimized design. If there is no satisfactory result, the engineering designer can modify the design and submit a new one. The use of this template, in practice, is limited to products or components that require only minor changes from version to version. The load cases must also be within certain limits. Because the user of the template has limited knowledge of design analysis and cannot affect the analysis, the final design should be inspected by a design analyst. Moreover, the engineering designer might need some support in interpreting the analysis results. To that end, guidelines and supervision by an analyst are available. The development of such templates requires extensive work in order to ensure good quality of the result. The development of the fully automated level approach, in most cases, is developed by an external resource such as an academic institution or a consulting company.

Such a fully automated template was developed in a research project during 2011-2012, in which an existing computer-based design analysis system, previously developed as a part of a research project in Swedish industry and academy, has been utilized as a background case. A full description of the system for which the design system was developed is given in [5]. It should be noted that the outcome of this project was a working, fully automated design system. The purpose was to facilitate the development of lightweight grippers (lifting device), the weight of which should be decreased to make it possible to use standard robots. A new lightweight gripper would be required for each new truck version. A production cell is shown Figure 17. Some possible gripper variants are presented in Figure 18.

Figure 17. The production cell [18]

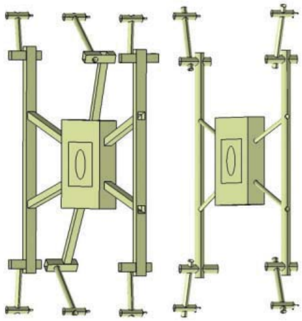

Figure 18. Possible variants of the gripper base

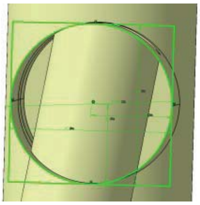

Figure 19. Implementation of the round and rectangular cross sections of the gripper

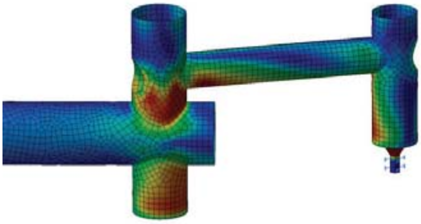

Figure 20. Detailed view of the deformation analysis result for the gripper base

As the production engineers, responsible for the gripper design have limited knowledge and experience of design analysis and limited experience of engineering design, an automated design system was developed for that purpose [18]. The design system is organized around 3 main elements called 1) the reference geometry model—input information about the body-in-white design to be picked up by the gripper; 2) the geometric model— all information about the geometry of the gripper base: the different parts and the rules about their possible configurations (see e.g. Figure 19; and Figure 20); and 3) the analysis model—information necessary to define and perform the structural design analysis: material properties, mesh discretization, boundary conditions and loading.

Types of analysis

Linear static and non-linear analysis is where the TBDA is used most frequently, see Figure 21. Both in linear static and non-linear static analysis it is possible to implement TBDA at many different levels and with different types of limitations and/or quality checks. There were a high number of TBDA systems including optimization. It might be surprising at first, but the extra cost and time of also implementing some optimization together with the development of a template are reasonable.

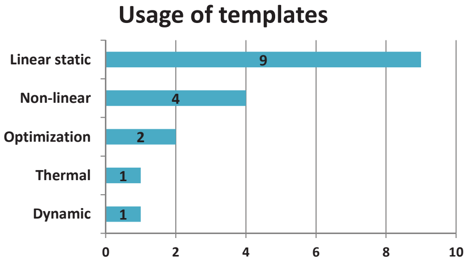

Figure 21. Types of analysis performed with TBDA

The linear static analysis is more often implemented for the basic and semi-automated levels. Logically, the fully automated level is suitable for the implementation of optimization, see Figure 22.One respondents did not use TBDA at any level.

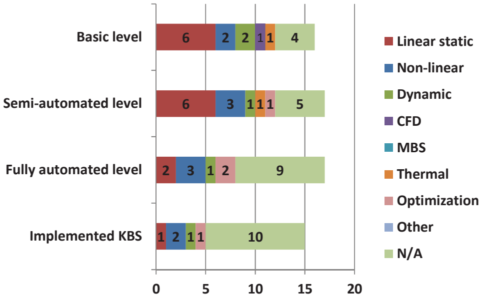

Figure 22. Types of analysis for different levels of TBDA

Role of TBDA in the overall development process

TBDA is naturally tightly connected with design analysis activities. Together with the TBDA, most often guidelines and support from an analyst are used as extra support. The guidelines help the engineering designer to set up the boundary conditions and other product related properties as it can contain information from, for example, physical testing.

Most of the companies that answered that they use TBDA have done so in the form of pilot projects. In some of those it has been done with a real product developed to be used as a commercial product; there are companies that use a basic level approach on a daily basis. TBDA is useful and valuable to use in some types of analysis but not in all. E.g. linear and non-linear analysis and optimization are suitable for TBDA.

The most valuable outcome of the pilot project with TBDA is enhanced concept generation and a higher technical knowledge of the product. It is also clear that the respondent companies are planning on full implementation of TBDA where possible. To be able to take full advantage of TBDA there are some processes around TBDA that have to be taken care of before the implementation of TBDA. In some of the respondent companies, there are still questions to be solved by the management, and one question is how to save the data generated.

Therefore, it is currently not easy to get a clear picture of TBDA and its role in the product development process. Some companies answer that they have a fully integrated design and analysis process, other ones that the product development process has been updated to also include design analysis and its process. TBDA could easily be made part of it. From the QA aspect, all results obtained from the TBDA are discussed with the design analyst and/or with the person responsible at the department, and the results are then finally approved.

DEVELOPMENT AND IMPLEMENTATION OF TBDA

The development of the templates, in some cases, has been done by academic institutions in direct collaboration with engineers at the target company, or with the help of an external source or resources inside the company. When an external consultant is used, the development time may vary depending on the workload at that time. If the company chooses to develop the TBDA within the company, there are many factors that have to be accounted for, one of them being that a dedicated project with its own budget and personnel must be created. It is also interesting to notice that, for most companies interviewed, there is a dedicated person or group at the company level that is responsible for both the TBDA implementation and the training/education provided to their engineering designers. This group also discusses with the design analysis department and/or the person responsible for that department in what project or for which product TBDA is to be used. The main reason for the decision to implement TBDA is to shorten lead time, to achieve better technical understanding of the product and to minimize the iteration time between the engineering designers and the design analysis departments. One important factor is the total cost of developing TBDA. Licenses, adaptation of software, implementation of TBDA and any education/training of engineers are all factors that must be taken into account when evaluating the benefits of TBDA obtained.

Engineering designers performed CBDA prior to the TBDA implementation. As this usage was more of an activity for interested engineering designers and the company had little control of it, decisions have been made to ensure that there is a company standard for the usage and implementation of TBDA. Furthermore, TBDA is valuable when companies do development work on different sites. Instead of sending information in text documents, it is very easy for the developer of TBDA to update the TBDA with new information. Many of the international companies use some sort of Product Data Management (PDM) or Product Lifecycle Management (PLM) system where the templates, input and output can be stored. Another aspect to have in mind when developing and implementing TBDA is the time. Not all companies have the resources needed for this type of enhancement. In some of the companies, a few persons have been working on this for a long time, improved the functionality during the usage and gained experience. In other companies they have chosen to enlist the help of an academic institution.

The implementation of support tools like TBDA requires good planning. As TBDA is implemented as a help for the engineering designers while performing design analysis, it is important that “such computer support should be cooperative, subordinate, flexible and useful” [19]. It is important to have this in mind when it is developed and implemented.

Training and knowledge pre-requisites for the engineering designer

Some of the engineering designers that have been using CBDA and now have used TBDA have been part of an internal training program. Such programs are traditionally connected with the generation of geometrical features, but there is also a basic course within the CAD-integrated FE software. There is a wish from the companies that the engineering designers who are going to use TBDA should have to pass the basic course for the integrated FE software. Some of the companies are now in the process of developing a new type of education/training that is directly connected with TBDA and design analysis. To raise the knowledge of these matters within the field of mechanical engineering in general, education/training for a wider circle of staff is also part of the program. Both internal and external resources are used for the education and training programs and there is also collaboration with universities within this field. The pre-requisites to be allowed to perform TBDA are at the same level as for an engineering designer. In most companies, a 3-5 year university program within the area of mechanical engineering is necessary.

IMPACT OF THE USE OF TBDA

For the engineering designer

In the companies interviewed, several engineering designers were already familiar with design analysis, and the introduction of TBDA was actually not appreciated by all engineering designers, as TBDA entailed limitations in their use of design analysis. However, after the introduction of TBDA, engineering designers in general are pleased with the functionality and the outcomes. The survey answers confirm this statement (Figure 23). Some of them have raised their skills both in general design but also in design analysis with the result that the technical knowledge of the product has become higher and thus generated products with a higher product quality.

For the design analyst

Traditionally, during development, the engineering designers send geometrical models to the design analysis department for evaluation against the mechanical properties. One recurring problem has been that the models have not always been mature or adapted for analysis. By introducing CBDA and TBDA, the design analysts have noticed a clear increase of competence in the technical knowledge (see Figure 23). Consequently, the models to be analyzed have generally been at a higher state of maturity, without any demands for modification by the calculation engineer. Moreover, the engineering designers understand better the possibilities and limitations of design analysis and make a more efficient use of the analyses. But as the engineering designers now have a better technical knowledge, a more technical discussion between them can take place. For example, it is now possible to have a deeper discussion about boundary conditions, materials and other technical analysis features than before.

Contrary to what was hypothesized at the beginning of this study, the total number of iterations between the engineering designer and the design analyst has increased. But as a result of higher training in design analysis, more valuable analysis tasks are ordered, resulting in products with better quality.

It is interesting that the design analysts in the companies interviewed are now pushing for an extended implementation of CBDA, especially TBDA. A few years ago, the opposite was true.

For the company

While the overall rating of the use of templates is not higher than that of the other types of support (Figure 12), the overall result is that the companies interviewed are pleased with this type of support for the engineering designers, and further development and implementation are planned in most of those companies.

In the companies that have information and experience of TBDA, it is clear that by introducing TBDA, some benefits have been reached. Most importantly, it is now possible to make more concept candidates and to perform more extensive evaluations of the concepts. A higher understanding of the product is another result. As knowledge about the product rises, the quality of the product also increases. In different pilot projects it was reported that the outcome was so satisfying that it resulted in less physical testing and reduced the total cost for the product. All the companies participating in the survey have experienced improvements in both lead times and quality of the design (Figure 23). The time saved through the help of TBDA was used by the companies interviewed to extend the time for concept generations.

In combination with TBDA, guidelines and some sort of super user (senior engineer or analyst) are used. By introducing TBDA, the companies have found out that there are some other things that have to be improved, among others, the use of PDM/PLM systems. As the usage of TBDA and analysis in general increases, a large amount of digital information needs to be stored, and strategic decisions have to be made on whether it is necessary to save all information.

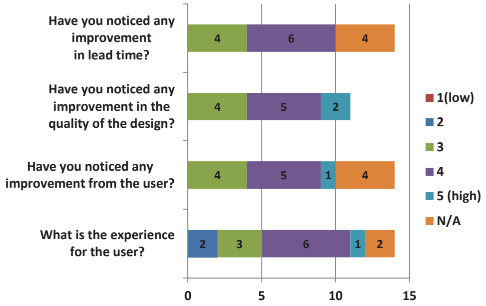

Figure 23. Experienced improvements through TBDA

Costs

The information received from the companies indicates that although they can predict the product cost, they do not yet have a clear picture of the total costs for developing and implementing TBDA. As was mentioned before, all companies are in an early stage and conducting some pilot projects for evaluation. If and when the companies decide to implement TBDA for full usage, one vital factor is the cost of licenses. When implementing TBDA, advanced features must be used and the license costs for these functionalities are rather high. Some companies experience such license problems; it is hard to understand what type of license is needed depending on what type of automation level is used. Moreover, investment in an introduction and/or specially developed training program for the users might be needed.

Next step

All of the companies that have provided information about TBDA are very clear that the implementation is going to continue. Some pilot projects have been finished and there are some ongoing projects that have to be evaluated. The highest priority is to cut the lead time for the whole product, but there is also a demand for lighter products and increased product quality. The main issue now is to review the results from the pilot projects and to review all the processes involved and to adapt them for the full implementation of TBDA.

New CAD/CAE methods that are more suited for TBDA and some other processes that are affected by the TBDA have to be developed to fully support the implementation of TBDA. To be able to handle this new challenge, changes have to be made also at the organization level.

Companies that have not implemented CBDA

Some companies do not plan to implement CBDA, and therefore nor TBDA, for their engineering designers. According to [1], 45% of the companies do not plan for their engineering designers to perform design analysis in the near future. However, in the new survey, 38% answered that it has not been implemented yet (Figure 24), which could mean that they are considering it or have started to think about it. The main reasons for not implementing it are described in Figure 24. One of the main arguments is that the cost is deemed too high, the respondents stating that the return-on-investment was too low. In some companies, it is company policy that the design analysis department performs and has the responsibility for all design analysis activities within the company. Also legal requirements or other standards may prevent the companies from delegating design analysis to engineering designers. Companies also argue that the engineering designer's work should focus on designing new products and that he/she lacks pre-requisites in mathematics and material engineering.

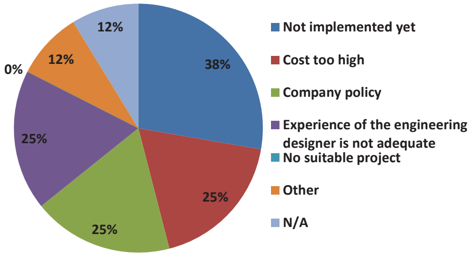

Figure 24. Justifications for not introducing CBDA

A practical difficulty that may also limit the development of TBDA is that it requires software that has the features needed for TBDA. Basic level templates require advanced design analysis tools. For semi-automated and automated templates, KBS and other systems might be required. The company might need to update their current solutions or change their CAD/CAE systems, which is a strategic question.

CONCLUSIONS

The positive outcomes that have been experienced by companies using TBDA are:

- The engineering designer has gained better technical understanding of the products.
- Fewer physical tests are required, which means economical savings.
- The engineering designers have increased their understanding of design analysis.
- The design analysis department is positive to the implementation of TBDA and wants it as soon as possible.
- The number of iterations between the engineering and analysis departments has increased, but as a result of the engineering designer's higher knowledge within design analysis there are better analyses and better products.
- The analysis department does not have to prepare the analysis models before analysis to the same extent as before the introduction.
- Some companies plan to implement TBDA as soon as possible.
- There has been an increase in the number of concept candidates generated.
- The overall product quality has improved.
- The company is introducing new methods to ensure that all analyses are performed according to the same standard.
- A new standard for education/training to be offered to their engineering designers is being developed.
- The answers obtained during the interviews were well correlated to the answers previously given in the online surveys by each of the interviewed companies. This indicates that this is probably also the case for the answers obtained from those companies only responding to the online survey.

Both the companies and the users have given the usage of templates the lowest score among the CBDA types of support for engineering designers (Figure 12 and Figure 13). This can be explained by the fact that it is a less proven type of support. The tools used within KBS, e.g. design table, formulas, Visual Basic and parameters, are dependent on integrated processes and some experience on the part of the user. Still, the companies interviewed were very positive towards TBDA. A definitive explanation to this paradox could not be found.

An interesting topic for further research is to develop TBDA systems that can be used across different development phases (for example both concept and detailed design phases). Even if optimization is integrated in several templates, focus has been on design analysis. From the survey, there are indications that there is a need for further development towards more synthesis aspects, that is systems that would take into account both design synthesis and analysis, enlarging the TBDA concept to template based design synthesis and analysis.

Another issue is integration with PDM/PLM. If PDM/PLM is used, the effects of using TBDA reach even further. As TBDA is a type of template, changes to the template can be made directly within the PDM/PLM system, and all users will then have updated templates available directly, independently of their location. There are problematic areas which need further attention. For example, it is necessary to develop new methods that include all sub-processes, e.g. how to create geometry suitable for the analysis model and how to store generated data in the PDM/PLM system.

The interview and the new survey answers, as well as the cases presented in this paper can be used by other companies (and by researchers) as decision support for whether TBDA for engineering designers makes sense for their business, and as guidelines if they want to implement TBDA. TBDA for engineering designers is not developed enough for anyone to make validated statements about the pre-requisites for adoption of the approach and conditions of success. Nevertheless information from the interviews shows that the implementation will continue.

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