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Eriksson, Martin

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Fundamentals of a Methodology for Predictive Design Analysis

Martin Eriksson

DOCTORAL DISSERTATION
by due permission of the Faculty of Engineering LTH, Lund University, Sweden.
To be defended at Lecture Hall Stora Hörsalen, Ingvar Kamprad Designcentrum, Sölvegatan 26 Lund. Date December 11, 2015 at 09.15 a.m.

Faculty opponent
Univ.-Prof. Dr.-Ing. habil. Manfred Zehn, Technische Universität Berlin
Abstract

The rapid development of computer-based design analysis tools and methods such as the finite element method (FEM) within computational structural mechanics (CSM), computational fluid dynamics (CFD), and multi-body systems (MBS), during recent decades has fundamentally changed the way in which products are designed and developed. Among the many advantages observed in industrial practice, one can mention: improved understanding of product properties and behavior, the possibility to optimize critical design parameters and to optimize parts as well as the entire product at a system level, the possibility to explore a design space during the synthesis activity and a decrease of the need for physical testing and thus of the number of physical prototypes needed. However, all of these opportunities to improve the performance and durability of the product-to-be come with challenges. In order to utilize these tools as efficiently and effectively as possible, it is necessary to facilitate their integration into the engineering design process, and into the product development and product innovation as a whole. Where computer-based design analysis replaces more traditional evaluation, validation and prediction methods, there is also a demand for greater confidence in the design analysis process and in the established results.

The objective set out for the research project presented in this thesis is to outline the fundamentals of a methodology for predictive design analysis (PDA), a computer-based design analysis methodology allowing for increased confidence in the predictions resulting from the design analysis activities regarding the critical design parameters and their influence on the behavior of the product-to-be (artifact) throughout the entire design and development of the artifact. The methodology is articulated around the generic design analysis (GDA) process model and how the activities within the phases of this process are influenced by factors emanating from the environment in which the design analysis task is originated and executed. Furthermore, a number of confidence appraisal activities (CAAs) are established to ascertain the confidence in the predictions made for the design analysis task during the analysis process. These provide for an increase in confidence in the design analysis process as well as in the results obtained as input to the subsequent engineering activities within the development project. The fundamentals in terms of constituent parts of a methodology for PDA, introduced in this thesis, are developed at a level of concretization that makes them directly applicable in an industrial setting.

Keywords: Predictive design analysis, Generic design analysis process model, Confidence appraisal activities, Computer-based design analysis, Engineering design, Integration
Fundamentals of a Methodology for Predictive Design Analysis

Martin Eriksson
To My family
Acknowledgments

The research work in this thesis has been a long and sometimes bumpy road towards the final goal. I would here like to take the opportunity to thank Åke Burman, formerly my main advisor, currently my manager, for introducing me to and training me in the aspects of design analysis. Your experience and input to our many discussions have been valuable for my professional understanding and development.

Robert Bjärnemo, currently my main advisor, has made all this possible by guiding me through the process. Robert, without your encouragement, support, and endless willingness to discuss the research field of engineering design in general and my topics in particular this thesis would not be completed. To my assistant advisor Damien Motte I want to express gratitude for your knowledge, tireless support and determination in our common research activities that have contributed to the completion of this thesis. And thanks also to Håkan Petersson, a fellow PhD student at the Division of Machine Design, for fruitful and constructive collaboration.

I would like to express my sincere thanks to my colleagues for interesting discussions, sharing valuable insights and experiences while coping with the challenges we have faced together, which has greatly contributed to the progression of the content of this thesis. I gratefuly thank and acknowledge professionals I have had the opportunity to work with in industrial endeavors over the years who, by continuously encouraging and pushing me to broaden my perspective and to learn more about design analysis and its use in industrial practice, have contributed to shaping this thesis.

To all my friends and family I would like to express heartfelt thanks for always being there, for sharing moments of joy and for showing me other values of life.

Last and most important: my thanks to my live-in girlfriend, Malena, for all your love, your never-ending support and never-questioning confidence that I would finish this thesis. Alvina and Niva, my two wonderful daughters, you are making my life complete and I am sending a boundless bear hug to you for your undemanding love that has given me much needed encouragement to complete this work.

Lund, November 2015

Martin Eriksson
Populärvetenskaplig sammanfattning

För datorbaserade konstruktionsanalyser används traditionella CAE-verktyg såsom finita elementmetoden (FEM) inom strukturanalys, datorbaserad strömningsanalys och stelkroppsdynamik. Behovet av predikteringar i produktutveckling och konstruktion utgår ifrån det faktum att man i början av utvecklingsprocessen har liten eller ingen kunskap om den blivande produktens egenskaper och speciellt inte om de förutsättningar som konstruktionsanalyserna ska baseras på. Allteftersom produkten utvecklas ökar kunskapen om produkten och om de förutsättningarna som analyserna baseras på och därmed också gjorda predikteringar. Avhandlingen fokuserar på en operationell integration mellan datorbaserad konstruktionsanalys och konstruktion för att öka tillförlitligheten i predikteringar av produkter; här begränsade till sådana som baseras på mekaniska verkningsätt.

Avhandlingen presenterar en metodik för prediktiv konstruktionsanalys (PDA – predictive design analysis) som baseras på en processmodell för konstruktionsanalys, (GDA – generic design analysis) innehållande tre faser; planering, utförande och rapportering, som lämpar sig väl för integration med olika konstruktionsprocessmodeller i industrin och akademien genom sin generiska karaktär.

I planeringen, utförandet och rapporteringen av konstruktionsanalysuppgifter måste man i industriella tillämpningar, nästan undantagslös, också beakta ett antal faktorer som påverkar analysens utförande. PDA-metodiken beaktar vikten av att identifiera och agera utifrån sådana faktorer, under beaktande av de osäkerhets- och felkällor som är kopplade till dessa, då dessa faktorer bidrar till ökad eller minskad tillförlitlighet i gjorda predikteringar. För att inkludera dessa faktorer och tillhörande osäkerheter och felkällor har ett antal aktiviteter benämnda CAA (för confidence appraisal activities), utvecklats och inkluderats i PDA-metodiken.

**Nyckelord:** Prediktiv konstruktionsanalys, generisk processmodell för konstruktionsanalys, tillförlitlighetsaktiviteter, Datorbaserad konstruktionsanalys, konstruktion, integration.
Abstract

The rapid development of computer-based design analysis tools and methods such as the finite element method (FEM) within computational structural mechanics (CSM), computational fluid dynamics (CFD), and multi-body systems (MBS) during recent decades has fundamentally changed the way in which products are designed and developed. Among the many advantages observed in industrial practice, one can mention improved understanding of product properties and behavior, the possibility to optimize critical design parameters and to optimize parts as well as the entire product at a system level, the possibility to explore a design space during the synthesis activity, and a decrease of the need for physical testing and thus of the number of physical prototypes needed. However, all of these opportunities to improve the performance and durability of the product-to-be come with challenges. In order to utilize these tools as efficiently and effectively as possible it is necessary to facilitate their integration into the engineering design process, and in product development and product innovation as a whole. Where computer-based design analysis replaces more traditional evaluation, validation and prediction methods, there is also a demand for greater confidence in the design analysis process and in the results obtained.

The objective set out for the research project presented in this thesis is to outline the fundamentals of a methodology for predictive design analysis (PDA), a computer based design analysis methodology allowing for increased confidence in the predictions resulting from the design analysis activities regarding the critical design parameters and their influence on the behavior of the product-to-be (artifact) throughout the entire design and development of the artifact. The methodology is articulated around the generic design analysis (GDA) process model and how the activities within the phases of this process are influenced by factors emanating from the environment in which the design analysis task is originated and executed. Furthermore, a number of confidence appraisal activities (CAAs) are established to ascertain the confidence in the predictions made for the design analysis task during the analysis process. These activities provide for an increase in confidence in the design analysis process as well as in the results obtained as input to the subsequent engineering activities within the development project. The fundamentals in terms of
constituent parts of a methodology for PDA, introduced in this thesis, are developed at a level of concretization that makes them directly applicable in an industrial setting.

**Keywords:** Predictive design analysis, Generic design analysis process model, Confidence appraisal activities, Computer-based design analysis, Engineering design, Integration
Appended publications

This thesis includes the following appended publications:

**Paper I**

**Paper II**

**Paper III**

Martin Eriksson is responsible for the development of the methodology presented. Martin Eriksson and Damien Motte have contributed jointly to the structuring of the publication. Martin Eriksson presented the paper at the conference.

**Paper IV**

Martin Eriksson is responsible for the development of the methodology presented. Martin Eriksson and Damien Motte have contributed jointly to the structuring of the publication. Martin Eriksson presented the paper at the conference.

**Paper V**
Eriksson, M., Petersson, H., Bjärnemo, R., & Motte, D., 2014, Interaction between computer-based design analysis activities and the engineering design process - An

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

**Paper VI**

Martin Eriksson, Damien Motte, Håkan Petersson and Robert Bjärnemo have contributed jointly to the literature survey presented in the publication. Damien Motte is responsible for the paper structure. Damien Motte presented the paper at the conference.

**Paper VII**

**Paper VIII**
Eriksson, M., Bjärnemo, R., Petersson, H., & Motte, D., 2015, A process model for enhanced integration between computer-based design analysis and engineering design. Submitted to the *Journal of Engineering Design*.

Martin Eriksson is responsible for the development of the process model presented. Robert Bjärnemo has contributed to the aspects of integration from an engineering design perspective and Martin Eriksson from a design analysis perspective discussed in the publication. Håkan Petersson contributed to the section on method development activities. Damien Motte reviewed the publication.
Other selected publications related to the PDA methodology published by the author but not included in this thesis


¹ Surname is now Jansell.
Other publications published by the author not included in this thesis


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2 Surname is now Jansell.


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Paper II: Establishment of a foundation for predictive design analysis within the engineering design process

Paper III: Investigation of the exogenous factors affecting the design analysis process

Paper IV: An integrative design analysis process model with considerations from quality assurance

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

Paper VI: Integration of the computer-based design analysis activity in the engineering design process – A literature survey

Paper VII: The methodology of predictive design analysis

Paper VIII: A process model for enhanced integration between computer-based design analysis and engineering design
List of acronyms and abbreviations

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<tr>
<th>Acronym</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>BEM</td>
<td>boundary element method</td>
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<tr>
<td>CAA</td>
<td>confidence appraisal activity</td>
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<td>CAD</td>
<td>computer aided design</td>
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<tr>
<td>CAE</td>
<td>computer aided engineering</td>
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<td>CAM</td>
<td>computer aided manufacturing</td>
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<td>CAX</td>
<td>computer aided technologies</td>
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<tr>
<td>CBDA</td>
<td>computer-based design analysis</td>
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<tr>
<td>CFD</td>
<td>computational fluid dynamics</td>
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<tr>
<td>CSM</td>
<td>computational structural mechanics</td>
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<tr>
<td>DOE</td>
<td>design of experiments</td>
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<tr>
<td>EC</td>
<td>engineering consulting</td>
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<td>ED</td>
<td>engineering design</td>
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<tr>
<td>EDM</td>
<td>engineering data management</td>
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<tr>
<td>EFG</td>
<td>element-free Galerkin</td>
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<td>FEA</td>
<td>finite element analysis</td>
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<tr>
<td>FEM</td>
<td>finite element method</td>
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<td>FSI</td>
<td>fluid structure interaction</td>
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<td>GDA</td>
<td>generic design analysis</td>
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<tr>
<td>HCF</td>
<td>high cycle fatigue</td>
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<tr>
<td>KBE</td>
<td>knowledge-based engineering</td>
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<tr>
<td>MBS</td>
<td>multi-body systems</td>
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<td>MC</td>
<td>Monte Carlo</td>
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</table>
NAFEMS originally the National Agency for Finite Element Methods and Standards, now the International Association for the Engineering Modelling, Analysis and Simulation Community

PD  product development
PDA  predictive design analysis
PDF  probability density function
PI  product innovation
PIRT  phenomena identification and ranking table
PN  production
PP  product planning
QA  quality assurance
QC  quality control
RSM  response surface methodology
SC  self-check
SME  small and medium-sized enterprises
VDI  Verein Deutscher Ingenieure, in English: Association of German Engineers
V&V  verification and validation
1 Introduction

In this chapter, the background introduces the concept of computer-based design analysis, followed by an account of research activities promoting the introduction of predictions in design analysis activities and a discussion of confidence in predictions. This is followed by the outline of the main research objective and the sub objectives deduced from it, its delimitations, the research process, and the outline of the thesis.

1.1 Background

During recent decades the rapid development of computer-based design analysis methods and tools has fundamentally changed the way in which products are designed and developed. The implementation and application of these methods and tools into industrial practice is here referred to as computer-based design analysis (CBDA) or design analysis for short. 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 the utilization of advanced, computer-intensive computational methods and tools emanating from the concept of computer aided engineering (CAE), such as computational structural mechanics (CSM), computational fluid dynamics (CFD) and multi-body systems (MBS) for the analysis of products based on one or more mechanical working principles. CSM is a common denominator for methods and tools applicable for evaluation of structural problems including the finite element method (FEM), the boundary element method (BEM) and meshless methods such as the element-free Galerkin (EFG).

Among the many advantages observed in industrial practice from introducing design analysis, one can mention: improved understanding of product properties and behavior, the possibility to optimize critical design parameters and to optimize parts as well as the entire product at a system level, the possibility to explore the actual design space during the design synthesis activities and to contribute to a decrease of the need for physical testing, and thus the number of physical prototypes needed. Another advantage, observed in an industrial survey by King, Jones and Simner
is the possibility to increase the number of design iterations in the same development time.

Design analysis is utilized today throughout the entire engineering design process and thus on all levels of concretization of the product-to-be. The engineering design process is here considered to be the core sub process of the product development process, and is joined by the product planning and production/manufacturing/production processes to constitute the sub processes of the overall product innovation process – see Section 2.1 for an elaboration on the interactions among these processes.

The increasing demands on manufacturing/product developing enterprises to meet the intensive competition on domestic as well as global markets have initiated the need for improved mapping, deployment and better understanding of the potentials design analysis might provide. More efficient tools, improved techniques and enhanced methodologies will enrich the business benefits and the return on investments made in design analysis. The number of publications available on design analysis is extensive, ranging from fundamental research on methods such as FEM to recommendations on the use of analysis for specific purposes as well as on generic analysis process models. However, the main focus is often set on the analysis task as such with the intention of providing means for supervising and increasing its effectiveness but neglecting its interaction with the engineering design task from which the analysis task originates. Engineering design is, in other words, merely seen as a provider of input to and receiver of the results of a design analysis task. Publications on the integration of engineering design and design analysis at a process level are therefore scarce and scattered; see Paper VI.

A similar lack of a broader perspective in this case of the interaction and integration of design analysis into the engineering design process (and thus into the product development process) is found in the mainstream literature, specifically in the textbooks, on engineering design and product development (Paper VI). One reason might be that research in product development has shifted increasingly towards synthesis (creative methods and cognitive studies of the engineering designer) and the contextual aspects of product development (activities linked to need finding, collaboration, and the like). According to Birkhofer (2011), because of the increasing specialization in these areas this trend is going to continue: “the worlds of Design Methodology and CAX technologies, with its models and procedures, increasingly draw apart”. Therefore, an effective integration of the design analysis into engineering design and product development as identified in (King et al., 2003; Knowles & Atkins, 2005; Newton, 2013) is today of the utmost importance.
1.2 Research activities promoting the introduction of predictions into the design analysis activities

During the 1980s and the early 1990s design analysis techniques such as finite element analysis (FEA) became important tools for evaluation and verification purposes of design solutions, especially, in industry. However, the difficulties associated with the introduction of FEA in industrial practice were many, and as a consequence of this development, additional costs became an economic burden in many analysis tasks. These factors reduced the use of FEA to such applications where geometry, load cases, materials, etc., were of such a complexity that traditional analytical methods provided no (or unreliable) results. The situation prompted research projects seeking to expand the use of FEA to include the early phases of engineering design activities. According to Bjärnemo and Burman (1999), the most significant advantage of applying design analysis early in the engineering design process was the shift from verification to predictive analysis, thus acknowledging the importance of foretelling the state of behavior of the product-to-be with greater accuracy and precision than provided by the traditional design analysis methods.

A proposal for not only extending the use of FEA to the early phases of the engineering design process but also utilizing FEA in design synthesis by means of an iterative procedure employing design optimization was presented in (Bjärnemo, Burman & Anker, 1993). An account of these methods and techniques and of a number of additional concepts for an extended use of FEA in the engineering design process is presented in (Burman, 1993a). These works clearly highlight the usefulness of introducing design analysis early in the engineering design process. Based on these results, the following objective was initially established for the concept of Predictive Design Analysis (PDA):

Development of computer-based tools for generating features of the product-to-be that are computationally obtainable on all levels of concretization throughout the mechanical engineering design process. (Bjärnemo & Burman, 1999, pp. 1794-1795)

Emanating from the uncertainties associated with design parameters and modelling of the product-to-be, especially during the early phases of the engineering design process, the introduction of statistical methods to handle them in FEA was proposed in (Eriksson, 1999). As a result of these studies, the role of design of experiments (DOE) was introduced as a part of the concept of PDA in (Eriksson & Burman, 1999). Additional contributions to the research were the introduction of PDA in an Internet environment (Eriksson & Burman, 2000) and a literature review on statistical methods in engineering design and design analysis (Eriksson, 1999).
1.3 Confidence in predictions

The increasing demands and constraints in planning, executing, controlling and monitoring of a design analysis task as well as in documenting and communicating the results obtained calls for improved integration of design analysis into the engineering design process, as well as an increased level of confidence in the design analysis process as such and in the results obtained. But this demand for an increased level of confidence requires development of appropriate tools and methods. Furthermore, in situations where design analysis is to replace more traditional validation and certification methods, an even greater confidence in the design analysis process and its results is required. This demand for increased confidence is a vital cornerstone in (and necessity for) assuring endorsement from management to invest in resources and expert knowledge facilitating a continuing extended use of design analysis in an industrial setting; see Adams (2006). Therefore the original concept of PDA must be further extended.

1.4 Research objective

The research project reported here takes its basis in the original outline of the concept of PDA, and aims at investigating and providing the fundamentals enabling the development of a full-blown methodology that empowers the utilization and benefits of design analysis to assure increased confidence in both the predictions of design parameters and their influence on the behavior of the product-to-be, and in the methodology as such. A methodology in this work is understood as follows: it consists of a process model that also encompasses a set of activities and their related methods, techniques and tools. The research within PDA also concurs with the perception of a possibility for increased utilization of design analysis tools within the engineering design process, which when introduced properly allow for design analysis to be a constituent part of future engineering design process and thus of the overall product development and product innovation processes. The motive for the approach is, in other words, to provide for the future establishment of an operational methodology that provides for the possibilities for an improved utilization of the full potential of design analysis within the engineering design process.

The MAIN RESEARCH OBJECTIVE set out for the research project is therefore formulated as follows:

*To outline the fundamentals of a methodology for predictive design analysis, a computer-based design analysis methodology allowing for increased confidence in*
the predictions resulting from the design analysis activities regarding design parameters and their influence on the behavior of the product-to-be (the artifact) throughout the entire design and development of the artifact.

This methodology for PDA, hereafter denoted the PDA methodology, should provide for an integrative environment between the actual design analysis activities and the engineering design activities as a part of the overall product development process, and of the product innovation process. Therefore the PDA methodology developed needs to be formulated and presented in such a way that it allows for incorporation and integration with other activities carried out during development of a product-to-be. Furthermore, the integration should be at an operational level facilitating adaptability to different industrial settings and design problems frequently occurring in industry. This results in the first research sub objective:

**To survey the aspects of integration of design analysis activities within engineering design, product development and product innovation.**

This PDA methodology should be presented as having an open-ended structure allowing for adaptation to specific engineering design process models presently utilized in industry, as well as similar process models found in literature. Therefore a generic design analysis (GDA) process model needs to be established that provides, at an operational level, an overall approach for planning and performing a general/generic design analysis task as well as for monitoring and communicating the obtained analysis results into the engineering design project – from which the design analysis task is originally derived. This results in the second research sub objective:

**To develop a generic design analysis process model that facilitates adaptability and integration of design analysis into engineering design, product development and product innovation at an operational level necessary to achieve confidence in its constituent elements.**

The circumstances in which the PDA activities are performed in an actual industrial setting are bounded by factors influencing the design analysis activities and their results. In order to fully utilize the potentials provided by the PDA methodology in an industrial setting, it is also necessary to consider the influence not only of the endogenous factors (factors directly connected with the design analysis basics) but also of the exogenous factors of the design analysis basics. Design analysis basics refers here to the principal elements of the design analysis model such as material, loads, and boundary conditions. This results in the third research sub objective:

**Investigate factors likely to affect and influence the design analysis activities, as well as the possibility to act upon them throughout the entire design analysis process.**

The understanding of uncertainties connected with these factors is important for providing insights to establish confidence in the decisions following the design
analysis task outcome. The PDA methodology thus needs to encompass a systematic handling of uncertainties connected with these factors throughout the entire design analysis process. This results in the fourth research sub objective:

*Explore systematic approaches for handling uncertainties connected with factors likely to influence the design analysis activities.*

It should, however, be noted that the handling of uncertainties is not the only part of a holistic view on confidence assessment. There is a need to identify and explore other confidence appraisal activities essential to the endorsement of confidence in design analysis activities within the PDA methodology. (All supporting activities, including handling of uncertainties, will hereafter be named confidence appraisal activities or CAAs). This results in the fifth research sub objective:

*Explore the activities beyond uncertainty handling that are essential to confidence appraisal throughout all of the design analysis activities.*

1.5 Delimitations

The mathematical formulations and implemented computational models generally used to illustrate PDA have mainly been confined to FEM since it is the most commonly used method within CSM, in both industry and in the research community, when addressing mechanical problems. Although design analysis is primarily considered in terms of mechanical properties, the open-ended structure allows it to be utilized for and in other disciplines of CAE analyses such as electromagnetic and fluid flow.

The thesis does not intend in any way to be regarded as a methodology for engineering design. It should instead be seen as providing complementary activities to existing engineering methodologies at an operational level, facilitating the use of design analysis as part of the overall activities within the engineering design process and thus of the product development process. Furthermore, it should be noted that PDA is a methodology that does not deal with the software integration of computer aided design (CAD) and CAE tools.

The thesis focuses on a practical utilization of design analysis activities during the engineering design process utilized for the product-to-be, and therefore it does not provide new findings of a basic research nature within any of the constituent parts of the PDA methodology. Instead it makes use of the findings within different research fields associated with design analysis as well as its accompanying activities to ascertain
confidence in the processes used and in the communicated results. These are outlined in the frame of reference.

Furthermore, while the PDA methodology is primarily developed with large and complex projects in mind, it can also be very useful as a guide for performing smaller and less complex projects.

One of the constituent parts of the PDA methodology is the establishment of a GDA process model. Even if the ambition when developing the GDA process model has been to offer an as broad and complete as possible approach to design analysis, fostering integration at an operational level, it is important to notice that activities and methods emanating from behavioural sciences have not been considered in depth, even if they might have an impact on the actual integration on a personal level.

1.6 Research process

The approach and process of the research has not been a linear progression in which all objectives were clearly stated from the beginning; rather it has been an iterative and evolving process, as indicated in Figure 1.1 where the timeline of papers connected to PDA are shown, in which the research focus has changed and the objectives matured over the years the research project has been carried out. This process is important for understanding how the different elements of the PDA methodology have been developed and what factors might have influenced this development. It will also help the reader understand the context in which the papers were written.

The early introduction of the author to the research field of numerical CAE methods occurred during his master’s thesis work at Carnegie Mellon University, Pittsburgh PA, USA that covered implementation of sensitivity analysis in the EFG method (Andersson & Eriksson, 1997). This, together with the ongoing research on PDA at the Department of Machine Design at Lund University, outlined in Section 1.2 initiated this research work with the following focus: Survey of applicable design analysis methods in combination with statistical DOE methods for introduction in early design phases for predictions of product design parameters. The survey resulted in Papers A, B and C, reported in a licentiate of engineering thesis (Eriksson, 1999).

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3 Surname is now Jansell.

4 Since 1999 Division of Machine Design.
At this point in time the author started to divide his professional life evenly between research at the Division of Machine Design and working as a design analyst, or analyst for short, in industry; primarily within structural analysis. During the next few years it became obvious to the author through performing design analysis in various projects within the automotive and offshore industry segments that FEM was the dominating method utilized and that design analyses were successfully applied for various purposes throughout the entire design and development of a product-to-be as well as during the use of the products. Insights from these projects led to a broadened research focus delving further into stochastic methods, since these were also frequently used in combination with FEM, especially during the later design phases. This resulted in the first refinement of the research focus: To consider the entire engineering design process and not only early phases, as well as including stochastic methods in combination with design analysis to study variability in design parameters.

This extended focus resulted in publications II and C. Paper II includes a brief state of the art review of statistical and stochastic approaches as well as an exemplification of how they can be used in different phases of the engineering design activities. Paper II also, although not elaborated on in depth at the time, initiated two vital elements presented in this thesis: it is important to deal with uncertainties connected with the analysis, and planning of the analysis is as important as the execution. Paper C presents the benefits of the utilization of design analysis in design activities as well as part of the assessment of physical testing of components and complete systems.

After the publication of Paper C, the research activities were given lower priority since the author was given the opportunity to be involved in a number of interesting, though challenging, projects within the aerospace industry involving both product development projects as well as method development projects. One of these projects, involving development of a method and an in-house tool for prioritization of design proposals in the early turbomachinery blade design work with respect to high cycle fatigue (HCF), was made public and is presented in Paper D.

Another insight from being involved in the projects within the aerospace industry was that the design analysis activities followed formalized processes for execution, often with more than one employee involved. However, the connection with other activities within product development on a process level was not as emphasized. This led to interest in conducting a survey, in a broader industry perspective, to investigate to what extent design analysis activities were integrated into product development. The survey is presented in Paper V. Furthermore, the incentive from Paper II for including uncertainty handling in the research in order to improve predictions also grew stronger during this period since this topic was, and still is, frequently addressed within both the aerospace and the offshore industries. In order to investigate the awareness and treatment of these uncertainties, they were also included as part of the
industry survey presented in Paper V. The results showed that handling of uncertainties was not yet completely integrated in the design analysis processes used. This resulted in another extension of the research focus: *To also include assessment of factors influencing the design analysis activities as well as uncertainties and potential errors connected with these.* In Paper III the assessment of exogenous factors influencing the activities of the design analysis process model is presented for different enterprise configurations that the author has been involved in.

From the industry survey it was also highlighted that although the companies interviewed had a quite clear view of the importance of design analysis for product development, it was still not a constituent part of their product development processes. This was also confirmed by the author’s own experiences as project manager of various design analysis projects involving different partners in various industry segments. This motivated the author to once again focus more on the research with an expanded scope: *To add the establishment of a design analysis process model facilitating the integration to product development.* Paper IV presents the initial version of the generic design analysis (GDA) process model, at the time denoted overall design analysis model, consisting of three phases: clarification, execution and completion. The process model was partly used as basis for the design analysis system presented in Paper E, focusing on the clarification phase, and Paper G, focusing on execution phases.

A further aspect that became evident while managing design analysis projects was the fact that a PDA methodology focusing on increasing confidence in the prediction was bound not only to uncertainty handling, but also to good process and quality control (QC) methods. This view was introduced in Paper IV through a set of review and control activities, denoted quality assurance (QA) aspects in the paper, such as QC, verification and validation (V&V) and uncertainties. In addition, an extensive systematic review, presented in Paper VI, of the works from the literature on engineering design methodology and design analysis covering the integration of the CBDA activity into the engineering design process was conducted to establish the state of the art.

Paper VII, which builds upon the findings in Paper VI, constitutes the first synthesis for PDA presented, and provides a systematic approach for handling uncertainties and potential errors related to design analysis activities in order to achieve confidence in the task performed. While developing this PDA methodology it became apparent to the author that further adaptations, additions and elucidations to the papers already presented would improve the methodology presented, which still at that point focused most on uncertainty handing. Therefore a new synthesis of the methodology is presented in Chapter 4 of the dissertation, together with further enhancements. The aspects of integration and adaption of the workflows in the GDA process model
activities into product development activities are further elaborated on in Paper VIII with exemplification of some design related problems often reoccurring in industry. In Figure 1.1 the progression of the research work is outlined by showing the connection of the papers connecting the PDA methodology to the sub objectives, denoted sob1 through sob5, as well as showing the publication dates of the papers.

**Figure 1.1. Timeline of papers connected with the PDA methodology. Lic: Licentiate of Engineering Thesis, PhD: PhD Thesis.**

1.7 Outline of the thesis

The thesis contains the following chapters (the thesis also includes eight appended papers):

*Chapter 1 – Introduction*

This chapter introduces the area of the research topic and its background, and establishes the research questions. The background of the research project is accounted for together with a description of the methodological approach and strategy chosen for the research project.

*Chapter 2 – Frame of reference*
This chapter presents the core research fields that form the frame of reference from which a PDA methodology should be developed.

Chapter 3 – Articulation of the different appended papers

This chapter provides an articulation of, and relation between, the different appended papers and the constituent elements of the PDA methodology presented.

Chapter 4 – Synthesis of the predictive design analysis methodology

This chapter provides an up-to-date synthesis of the PDA methodology and how it can be adapted to different industrial settings.

Chapter 5 – Conclusions and future research

The conclusions drawn from the research project are summarized and presented in this chapter, followed by a discussion of subjects for future research in this and related areas.

References

Appended papers
2 Frame of reference

The core research fields that constitute the frame of reference for this thesis are presented in this chapter. The first of these, presented in Section 2.1, focuses on the role of engineering design in the overall product innovation process, and thus also in its constituent sub processes: product planning, product development and production. In Section 2.2, existing design analysis process models are examined. A review of the current efforts made to establish integration between design analysis and engineering design, in theory as well as in industrial practice, is presented in Section 2.3. The uncertainties and errors emanating from design analysis in engineering design are elaborated upon in some detail in Section 2.4.

2.1 Engineering design and its role in the overall product innovation process

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 these, and probably the one which still today has had the most fundamental impact as a theoretical foundation from which a significant number of current engineering design and product development process 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 & 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 & 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 (A systematic approach to conceptual design) (VDI, 1977), but also in other countries as in the UK by Glegg (1972), French (1971) and Jones (1970) 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).

In the light of the importance of engineering design on the other processes involved in the development of products, it is essential to define engineering design at an operational level. In VDI guideline 2221 (VDI, 1993 p 40) the engineering design process is described as:

… totality of the activities with which all the information necessary for producing and operating a technical system or product is processed in accordance with the task. The result is a set of product documents.

In a somewhat more philosophical vision of design, Simon (1996) makes a comparison between science and design in which he 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.

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), Ulrich and Eppinger (2012) and last, but not least, in Pahl and Beitz (2007). It should be noted that the original engineering design process model by Pahl and Beitz is regarded today as a product development process. As noticed in (Motte, 2011 p 31), Pahl and Beitz’ chapter ‘Process of planning and designing’ (in the 1996 second translation of their book into English) is now renamed ‘Product development process’ (in the 2007 third English translation of the book).

This interrelation between engineering design and product development might seem confusing, but is the result of the generic engineering design process model determining the phases of the development process for the development of technical products, and the introduction of product planning. The ISO 9000:2005 standard states that:
The terms ‘design’ and ‘development’ are sometimes used synonymously and sometimes used to define stages of the overall design and development process (ISO, 2005, p 12).

Product planning, or alternatively Product renewal, is here considered as a pre-process to the actual product development process during which the following activities are carried out: 1) creating and/or finding opportunities in the form of product concepts, 2) evaluating these concepts in order to determine the most promising, 3) establishing a prioritization in time of the development projects – based on the selected product concepts and 4) the planning of the downstream product development activities (Ulrich & Eppinger, 2012). 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, and development of new platforms and improvements of existing products is 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 & Eppinger, 2012; Olsson, 1995; Wheelwright & Clark, 1992). In Figure 2.1 the engineering design process by Pahl and Beitz is presented.

Even though additional ways of structuring the product development as well as the engineering design process models are at hand, such as the funnel model by Wheelwright and Clark (1992) and axiomatic design by Suh (1990) for the engineering design process model, the product development 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.

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 et al., 1985; Ulrich & Eppinger, 2012); in the academic setting multifunctional is often referred to as multidisciplinary.
Figure 2.1 The engineering design process by Pahl and Beitz (2007 p 130).
The process presented by Olsson denoted *Integrated Product Development* (Olsson et al. 1985) involves four parallel activity chains (marketing, design, manufacturing/production, and business/financing) as described in Figure 2.2.

In Ulrich and Eppinger (2012), the design function has a broader perspective encompassing both engineering and industrial design. In the given context the focus is on engineering design. Among the additional functions frequently included in the product development processes are: research, legal affairs, sales or project management (Ulrich & Eppinger, 2012). In Figure 2.3 the generic development process by Ulrich and Eppinger (2012) is presented.

The initial engineering design activities, during which synthesis-oriented activities dominate, are mainly derived from the product planning process. Especially, the exploration of the design space for new concepts constitutes important engineering design related activities. Also post-product development activities, occurring during the production process, such as design of fixtures and other types of production equipment, involve engineering design activities. Note that an engineering design process model includes all of the steps or activities, starting from a specific material need to the final design of the product-to-be, including necessary documentation of the product and other necessary documents for the materialization, production/manufacturing, of the product-to-be, while engineering design activities only encompass parts or certain steps/activities of such a process.
Figure 2.3 Design process by Ulrich and Eppinger (2012).
To summarize: the sequential linking of product planning (PP), product development (PD) and production (PN) defines the overall product innovation (PI) process. All of the processes are illustrated in Figure 2.4 in which the engineering design process (ED process) and the engineering design activities (ED activities) are also included. The actual contents in each of the processes and activities in the PI process are not elaborated upon. The process models proposed in the literature advocate different contents; the contents are also specific to each company. Finally, a dashed double arrow indicates the upcoming integration between the PI process and the design analysis process model.

2.2 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 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 and Elkhodary (2014), Chopra (2012), Cook (1995), Cook, Malkus, Plesha and Witt (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 connected with FEM. Procedures connected with BEM can be found in e.g. Brebbia and Dominguez (1992) and Mukherjee (2005), and such procedures for meshless methods can be found in e.g. Belytschko, Lu and Gu (1994) and Liu (2003).

In the first of the three volumes by Zienkiewicz and Taylor (2005), a short history and background is outlined along with a thorough presentation of the FEA methodology as such. In Cook (1995) and Bathe (1996) the theoretical base for FEA is outlined together with discussions regarding modeling (such as approach, sanity checks and verification of results), errors and accuracy in FEA.
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 (paper VI). Below three examples of analysis processes are presented.

The analysis process model by (Bathe, 1996) presented in Figure 2.5, 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.
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 & Askenazi 1998; Gokhale, Deshpande, Bedekar & Thite, 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 & 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 estimates, etc. as shown in Figure 2.6. The workflow is concluded with information feedback in terms of presentation and reporting.

![Figure 2.6 Workflow of an FEA outlined by NAFEMS (Baguley & Hose, 1994).](image_url)
Adams and Askenazi (1998) discuss the basic steps in 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.

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

To summarize: as previously mentioned, the process models accounted for 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. However, as also mentioned previously, each of the phases is built up based on a number of activities or steps that are to a large extent also common in nature, but diverge according to the overall perspective adopted for the structuring of the individual process model. Examples of these activities/steps are the introduction of, and attempt to facilitate, interactions with overall processes and activities as the ED process, ED activities, and PI, PP, PD and PN processes – see Figure 2.7. 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 2.7 Illustration of the processes to be integrated.
2.3 Integration between design analysis and engineering design, in theory as well as in industrial practice

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 design analysis processes; and thus also between the overall processes in which engineering design is a sub process or activity – see Section 2.1. Integration of this nature is usually referred to as integration at 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 & Cash, 2015 p. 86). Some of the elements presented below are taken from Paper VI.

In a comprehensive literature survey by Burman in 1993 (Burman, 1993b), 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, efforts 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 an extensive literature survey carried out (paper VI) whose 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 this survey it was found that in sixteen textbooks on engineering design and development reviewed, among others (Dieter & Schmidt, 2013; French, 1998, Haik & Shanin, 2010; Otto & Wood, 2001; Ullman, 2010; Ulrich & Eppinger, 2012), design analysis is not emphasized in the engineering design and development process models. The exceptions are found in the German literature in works by Ehrlenspiel (1995), the German versions of Pahl and Beitz starting from the very first edition of 1977 (Pahl & Beitz, 1977), and the VDI guidelines 2221 of 1993 (VDI, 1993) and 2211-2 of 2003 (VDI, 2003). Ehrlenspiel (1995) mentions that design analysis and simulation are basic design activities for design proposal evaluation. Design analysis is mentioned in Pahl and Beitz (1977) 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 present 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 & Beitz, 1984). The VDI guideline 2221 of 1993 (VDI, 1993) presents the same model as Pahl and Beitz, who were among the main authors of the
guideline. The VDI guideline 2211-2 (VDI, 2003) provides recommendations on the use of design analysis within the engineering design process model presented in VDI guideline 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.

As mentioned in Section 2.2, 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.

The need for integration of engineering design and design analysis in industrial practice is well established. In an industry survey by Burman in 1992 (Burman, 1992), 3 of the 10 developing companies interviewed stated that they were using design analysis from the conceptual design phase and upwards, and point out the need for a more extensive use of design analysis in the engineering design process. Another survey in industry was carried out in 2001, within the NAFEMS-coordinated FENet project (Knowles & Atkins, 2005) with over 1300 respondents in more than 40 countries and from various industry sectors (although most answers came from experienced users of FEM in the UK and US). Although the scale, depth and maturity of FEA in different industry sectors varied widely, the FENet project extracted a number of common issues important for further focus on increased utilization of FEA technology, among other things aspects of the level of product development: “Integration of finite element technology and simulation into the wider business enterprise in order to deliver real business benefit”.

In a subsequent survey by NAFEMS, the NAFEMS Simulation Capability Survey 2013 (Newton, 2013), 1115 respondents point out that nowadays nearly 30% of the analyses are done during the conceptual design phase.

In an industry survey from 2003 including five companies by (King et al., 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 which 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 & Wakes (2005), general discussions about integration must be complete with practical guidelines. There are in effect several shortcomings regarding the traditional interaction models between the simulation and design activities. Concerning analysis planning, Ciarelli states (Ciarelli, 1990):

> 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)

Regarding the analysis execution, Ciarelli (1990) claims that the designer is not in control because of his/her limited knowledge of the simulation tools, their possibilities and limitations, 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, during result communication:

> 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)

Some practical guidelines dealing with planning can be found in Anker (1989), and in Tyrrell (1993). Most interesting, from an integration point of view, are 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) revealed 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 must necessarily 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 used at the conceptual design level, and shape optimization at the
detail design level. Furthermore (Albers & Nowicki, 2003) identify the ultimate goal of such integration, sometimes called simulation-driven design (Sellgren, 1999) or simulation-based design (Shephard, 2004).

Numerous publications have been focusing on this software integration at diverse levels: interoperability at feature level – CAD to CAE feature simplification and idealization (Dabke, Prabhakar & Sheppard, 1994; Stolt, 2005), CAE to CAD reconstruction (Belaziz, Bouras & Brun, 2000; Lee, 2005), new shape representation (Hamri, Giannini & Falcidieno, 2010), at a higher-information-level (Bajaj, Peak, & Paredis, 2007a; Bajaj, Peak, & Paredis, 2007b; Dolšak & 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 & Angelo, 2006) that concluded that interoperability among CAD/CAM/CAE systems suffers from problems that are mostly related to information loss and incompleteness during data exchange. This has also received 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, Vielhaber, Deubel, Weber & Haasis, 2005).

Thanks to increased software integration, the traditional frontier between design synthesis and design analysis that has been prominent in engineering design (Pahl & Beitz, 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 & Cagan, 2001; Cagan, Campbell, Finger & Tomiyama, 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 & Bonham, 2000). Nordin, Hopf, Motte, Bjärnemo and Eckhardt (2011) have developed a generative design system for a bookshelf whose structure is based on Voronoi diagrams; the structure evolves with the 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, Motte, Eriksson and Bjärnemo (2012), a computer-based design system for lightweight grippers has been developed that can be used by production engineers who possess very limited knowledge of and experience with design and analysis.

Additional aspects in support 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 QA in product development in sensitive areas, such as the automotive, aeronautical and defense industries. Certain analysis methods are
dictated by the company, by standards, regulations or by specific organizations; for example, analyses in the offshore industry are often quality-checked by a third party independent contractor 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 neither the literature on engineering design and product development nor in the literature on design analysis. Regardless of this lack of theoretical support, different forms of integration are practiced daily in industry as accounted for above. The problem of integration becomes even more complex when taking into account that such a process model not only needs to handle all procedural issues on an organizational level but also needs to be adaptive at an operational level in order to be linked to the different process models utilized in industrial practice. Since the structural decomposition of the design analysis models is mainly governed by the generic phases accounted for in Section 2.2, a generic design analysis process model is thus the best platform upon which an integrated process model can be built.

2.4 Uncertainties and errors

From an engineering point of view, uncertainties and errors are present in all areas of design (products, processes and organizations). As mentioned in the research objective in Section 1.4, uncertainties connected with these areas are important for providing insights to establish confidence in the decisions following the design analysis task outcomes. This section defines and characterizes uncertainties and errors as used in the description of the PDA methodology.

The definition of uncertainties adopted for the PDA methodology is based on a framework by Hastings and McManus (2004): “Uncertainties are things that are not known, or known only imprecisely.” An important aspect of this definition is that uncertainties can be associated either with a risk or with an opportunity. Risk is an undesirable resolution of an uncertainty. Opportunity, on the other hand, might exist if an uncertainty is resolved in a way favorable to the system.

Uncertainties are categorized based on their nature as being either aleatory or epistemic (Oberkampf, Helton, Joslyn, Wojtkiewicz, & Ferson, 2004).
- Aleatory uncertainty is used to describe the inherent variation associated with a physical system or product and also with the measuring devices utilized to monitor it.

- Epistemic uncertainty (the term originates from the Greek word *episteme* meaning knowledge) is on the other hand used to describe the possible lack of information or knowledge that is derived from some level of ignorance of the system or its environment or in any of activities and phases involved in performing the modeling and analysis or simulation of the system.

The management of uncertainties also strongly connects to the present state of knowledge of the design properties as displayed in Figure 2.8 by Nikolaidis (2004). The left picture in Figure 2.8 shows the possibility of improving the present state of knowledge by reducing the uncertainty. However, since most uncertainties are complex and include both an epistemic uncertainty, which is reducible, and an aleatory uncertainty, which is irreducible, an analysis outcome will always be bounded by some degree of uncertainty, as highlighted in the right picture in Figure 2.8.

This differentiation is operationally important, as the uncertainties associated with the endogenous factors influencing the design analysis task are mainly aleatory, while the uncertainties linked to the exogenous factors are often epistemic. The handling of these uncertainties during the analysis activity provides the possibility of mitigating actions for reducing the uncertainties.

![Figure 2.8. Illustration of uncertainty with regards to knowledge, taken from Nikolaidis (2004, Figure 8.5).](image)

Another source of potential deficiency in the outcome of the design analysis models utilized is the errors associated with the analysis task (Grebici, Wynn & Clarkson, 2008). The errors are defined as identifiable inaccuracies in any of the activities and phases of the modeling and execution of the design analysis model that are not due to lack of knowledge (Oberkampf, DeLand, Rutherford, Diegert & Alvin, 2002).

The potential errors identified are categorized as either acknowledged or unacknowledged (see Oberkampf et al., 2002 for further reading):

- Acknowledged errors are inaccuracies identifiable by the analysts.
- Unacknowledged errors are not identifiable by the analysts but are identifiable by other stakeholders.

The acknowledged errors might originate from decisions made regarding the design analysis at hand, such as the comprehensiveness of the design analysis model regarding the reality it imitates, or on restrictions on development resources. Thus the acknowledged errors are of such nature that the outcome of the design analysis depends on them, and they should therefore be given the fullest attention during review and monitoring of the outcome.

The second category of errors, which is independent of a deliberate decision, is the unacknowledged errors, which are built into a design analysis model without the knowledge of the analyst. This category of errors is much harder to estimate and evaluate in the review and monitoring processes of the analysis outcome, since the analyst is unaware of the extent to which these errors exist in the current model and of their influence on the outcome of the analysis. External knowledge/expertise and previous experience could serve as important sources of information when investigating and reviewing the existence of unacknowledged errors as well as how to assess them.

To summarize: the concepts of uncertainties and errors described above provide an operational foundation many elements of the PDA methodology can be built on. While most works within the design analysis community deal with uncertainty handling to mitigate risks (Chalupnik, Wynn & Clarkson, 2009), it is important to point out that a PDA methodology also facilitates the possibility to exploit opportunities associated with uncertainties.
3 Articulation of the different appended papers

The thesis comprises eight Papers I – VIII that constitute the foundation of this thesis. The links and congregations among these with regards to constituent elements of PDA are shown in Figure 3.1. The papers denominated A to F (p. xv) are related to this thesis but are of lesser importance and therefore not appended. It should be noted that the terminology and definitions used in the appended papers can be slightly different from the PDA synthesis outlined in Chapter 4. This is due to the fact that the methodology has evolved during the time of the research project and new perspectives have led to changes in the terminology.

Figure 3.1. Relations between the appended papers and the constituent elements of the presented PDA methodology.
3.1 Paper I: Efficient use of finite element analysis in early design phases

This paper gives an introduction to the PDA approach, as it was formulated in 1999, discussing the significant advantage of applying design analysis early in the engineering design process by adopting the shift from primarily verification analysis to predictive analysis. The paper presents the value of using the statistical method of DOE together with PDA within the engineering design process to evaluate conceptual solutions in the early engineering design phases, i.e. conceptual and embodiment design phases. A client/server implementation is presented and utilized to highlight the possibilities for engineering designers in different design teams connected to the Internet/intranet to view and evaluate the statistical result simultaneously – thus enabling the integration between the engineering designer and the analyst. Furthermore, the execution of the individual DOE analyses was performed on a distributed processing system, i.e. a cluster of computers connected through a network facilitating faster turnover times of the engineering design analysis tasks. The total evaluation time decreases rapidly when the number of computers utilized increases. The paper points out that using both design analysis and statistical methods at the early phases of the engineering design process, the proposed PDA approach will provide the engineering designer with tools for using design analysis more effectively.

3.2 Paper II: Establishment of a foundation for predictive design analysis within the engineering design process

In this paper the discussion of the statistical method of DOE in connection with PDA, presented in Paper I, is elaborated on in more detail together with discussions on stochastic approaches for uncertainty propagation. The benefits as well as the drawbacks of different methods and approaches are discussed, and the value of introducing the PDA activity within different phases of the engineering design process is outlined mainly in terms of statistics. The conclusion of the work presented in the paper is that with increasing computational capabilities and enhanced mathematical foundations (within DOE and uncertainty handling) the PDA approach will increase the probability for the engineering designer or analyst to make appropriate decisions, with higher confidence, throughout the entire engineering design process.
3.3 Paper III: Investigation of the exogenous factors affecting the design analysis process

This paper includes elaboration of factors influencing the design analysis task during a development project and how to handle them adequately. Furthermore, different enterprise configurations in which the design analysis activities take place are discussed. This work also shows that analysis cannot be considered as a black box in the engineering design process – a lot of interactions between the analyst and the engineering designer are necessary.

The factors presented are assumed to be present whatever the size and complexity of the project, and the presented guidelines are therefore deemed relevant both for large companies and for SMEs, even if these guidelines can be supplemented for specific organisations. It is furthermore noted that it is very difficult, if not impossible, to determine whether the presented set of factors is comprehensive or not, but one needs to focus on the factors that have the greatest impact on design analysis.

3.4 Paper IV: An integrative design analysis process model with considerations from quality assurance

This paper presents the initial version of the GDA process model that is one of the constituent elements of PDA methodology that implements several reviews and controls, denoted QA aspects in the paper, such as QC, V&V and uncertainties, allowing for a better integration of the design analysis activity in the overall engineering design process. An interesting result of the discussion in the paper is that V&V are not directly coupled, although they are almost always presented together in the literature. The process model is formulated as much as possible in general terms so that it can be adapted to different product development processes available in industry.
3.5 Paper V: Interaction between computer-based design analysis activities and the engineering design process – an industrial survey

This paper covers an industrial survey involving the heads of the design analysis or product development departments of 15 Swedish companies. To decrease, or to at least to some extent reduce the impact of the lack of a common terminology, while simultaneously providing the openness necessary to promote the explorative nature of the survey, a qualitative method based on semi-structured interviews was chosen. The survey technique chosen is based on a combination of questionnaire and interview that had already been proven successful in (Bjärnemo, 1991). The survey shows that 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. The response obtained from the participating companies indicated that in about 30% of them the engineering designers are taking an active part in the design analysis activities. It was moreover concluded that design analysis is utilized within different situations with different characteristics: 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. Another aspect that this study highlighted is that method development is present in many companies, but has not been emphasized in the literature.

The interviewed companies have quite a 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 considered, and the input 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 desired. Furthermore, CAAs such as V&V, uncertainty handling and the like are not yet completely integrated in the design analysis process within the interviewed companies.
3.6 Paper VI: Integration of the computer-based design analysis activity in the engineering design process – a literature survey

The objective of this paper is to present an extensive systematic review of the works from the literature on engineering design methodology and design analysis covering the integration of the design analysis activity into the engineering design process. Publications that have been reviewed cover both engineering design and design analysis for a period of more than 25 years. Based on this systematic investigation, it can be concluded that research on the integration of engineering design and design analysis at the process level is scarce and scattered. Furthermore, there are very few cross-references between research groups, and many stand-alone works. Only the German literature presents a greater continuity. The findings highlight the need for a more contextual design analysis activity. Thus there should be a large emphasis on design analysis planning, as well as on utilization of design analysis processes in various industrial situations. Valuable information regarding the CAAs, denoted QA aspects is also provided.

3.7 Paper VII: The methodology of predictive design analysis

The paper presents a first synthesis of the methodology of PDA with special attention given to the handling of uncertainty connected with the factors influencing the design analysis task. It is shown that taking uncertainties and potential errors into account, with dedicated techniques throughout the design analysis activities, is important in order to provide other stakeholders with confidence in the decisions based on the design analysis task outcome. Many of the elements of the PDA methodology are outlined and discussed in terms of the activities carried out to evaluate the product-to-be connected with the case study presented. The PDA methodology presented provides a systematic and well-founded guide for handling uncertainties and errors related to design analysis activities, which is emphasized by the case study. This allows for an increase in confidence in the design analysis process and results used in a development project.

Because the methodology has evolved since this first synthesis was presented, and because page limitation prevented more elaboration on the methodology, an up-to-date synthesis is presented in Chapter 4.
3.8 Paper VIII: A process model for enhanced integration between computer-based design analysis and engineering design

The paper presents the first version of the generic design analysis (GDA) process model that facilitates integration to the multitude of engineering design process models in industrial practice, including overall processes such as product innovation, product development. 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.

The presented GDA process model is adaptive and generic. The required adaptivity of the GDA process model is sufficiently accounted for by the matching on all levels of abstraction 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. 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.

The application of the GDA process model is exemplified by four examples, which have been utilized for validation of the process model.
4 Synthesis of the predictive design analysis methodology

This chapter presents a synthesis of the elements that together form the PDA methodology and that ensure an increased confidence in the predictions made within the design analysis activities.

The outline of this chapter is as follows: first the overall description of the GDA process model and its connection to the PI process is outlined, secondly the factors influencing a design analysis task are discussed, thirdly the CAAs are discussed followed by the detailed description of activities connected with the three phases of the GDA process model. The section concludes with a summary of the elements of the PDA methodology.

4.1 The generic design analysis (GDA) process model

The use of design analysis in the PI process involves specific issues. The analysis activity is often performed by an analyst employed by either the enterprise or an engineering consulting (EC) 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 task and the PI process is, in other words, significant for providing an increase of efficiency and effectiveness in the development and design of products. Therefore GDA process model is developed with the emphasis on the need for closer cooperation between engineering designers and analysts at an operational level to promote increased integration and thus an improved understanding between the two categories of specialists. The need for such a process model and supporting activities is not confined to industrial practice but also applies to the training of new generations of analysts and engineering designers. The GDA process model presented in Figure 4.1 is both adaptive and generic, which here should be interpreted as not being dependent on a specific PI process utilized by an enterprise nor on the specific type of product(s) developed by the enterprise.
Figure 4.1. The GDA process model with defined phases.

The overall description of the GDA process model is provided in Section 4.1.1, the integration aspects in Section 4.1.2.

4.1.1 Overall description of the activities of the GDA process model

The GDA process model consists of three phases: analysis task clarification, analysis task execution and analysis task completion, as well as the activities and sub activities constituting each of the phases; see Figure 4.2.

The analysis task clarification phase consisting of three activities is as important as the analysis execution and completion itself, because it is at that stage that vital aspects of the task at hand should be identified, discussed and agreed upon. In the identification of the task (activity 1a), the objective is to ascertain the task relevance and the actual need for the design analysis activity. Once the relevance of the task has been agreed upon and the decision has been taken to continue, the preparation of the task content brief takes place (activity 1b). I have chosen to separate the activity of preparation of the task content brief (activity 1b) from the activity of planning and agreement of the task (activity 1c) for two main reasons. First, the planning of the task can be done so as to fit with the concurrent product development activities. Second, there can be a certain period of time between the preparation activity and the moment the decision makers finally agree on the task, which may lead to discussions and late changes before the brief is finally accepted. Once all items, known and agreed upon at the time of preparing the document, are in place in the task content brief, the analysis activity should be carefully planned and a formal document should be prepared and mutually agreed on that forms the basis for the analysis execution (activity 1c). This should consist of detailed planning of the content described in the design analysis task content brief that has been established.

During the pre-processing (activity 2a) activity, the agreed task is processed further resulting in a representative engineering model (such as a geometrical model or a functional model) as well as the actual computational model for solution. In the next activity, solution processing (activity 2b), the analysis task is solved (executed) to generate the adequate amount of results needed for producing the required results. Results are extracted and assessed within the post-processing (activity 2c) with the purpose of providing adequate understanding of the general model behaviour as well as accuracy and convergence in results obtained. 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), design analysis project findings are being implemented into the engineering design task, from which it originates.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a. Identification of the task</td>
<td>1. Discussion around task relevance and need for a pre-study 2. Pre-study 3. Decision to perform analysis task 4. Establishment of initial task mission statement</td>
</tr>
<tr>
<td>1b. Preparation of the task content brief</td>
<td>1. Definition of the overall purpose of the task 2. Clarification of the task 3. Establishment of the task content brief</td>
</tr>
<tr>
<td>1c. Planning and agreement of the task</td>
<td>1. Detailed planning of the task 2. Discussion and negotiation of the task 3. Agreement or rejection of the task</td>
</tr>
<tr>
<td>2c. Post-processing</td>
<td>1. Extraction of solution results 2. Compilation of result information 3. Assessment of extracted results</td>
</tr>
<tr>
<td>3a. Results interpretation and evaluation</td>
<td>1. Results interpretation 2. Evaluation and conclusion of findings 3. Decision on the need for additional analysis</td>
</tr>
<tr>
<td>3b. Documentation and communication</td>
<td>1. Task documentation 2. Documentation of suggested design alterations 3. Communication of task findings and recommendations</td>
</tr>
<tr>
<td>3c. Integration of the results into the project</td>
<td>1. Implementation of task results and findings 2. Participation in decisions on implementation of design alterations 3. Contribution to further analysis tasks</td>
</tr>
</tbody>
</table>

Figure 4.2. The GDA process model with defined phases and core activities.

For each of the activities the core sets of sub activities are also presented in Figure 4.2. Note that awareness that the core sub activities are not always enough to cover all aspects in every foreseeable design analysis task results in adding additional sub activities when needed; denoted …-n. in Figure 4.2.
4.1.2 Integration in the engineering design and development process

The need for integration is 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. However, this does not exclude the need for a more or less continuous exchange of data and information between engineering designers and design analysts during all of the activities of the GDA process model. In Figure 4.3, the interaction activities within ED and the GDA process model are indicated by arrows. Note that the terminology used here regarding the involvement of engineering design into the PP process is ED activities, thus emphasizing that during the PP process the involvement of engineering design is of a fragmentary nature. The second arrow illustrates the more or less continuous interactions between the ED process, here considered as the core sub process PD process, and the GDA process model. Similarly the third arrow illustrates the interaction to the PN process.

![Diagram of GDA process model interactions](image.png)

Figure 4.3. The GDA process model the interactions (arrows) to the PI process, specifically to the ED activities during the PP and PN processes and to the ED process during the PD process.

It should furthermore be noted that the applicability of the GDA process model is independent of engineering design methods, techniques and tools utilized during the development of the design solution to be analyzed, facilitating adaptations to different situations in which it is utilized. In order to achieve this adaptability of the GDA process model, the constituent elements of the design analysis process, its phases and their corresponding activities, are required to 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 ED activities and process and thus also to the overall PP, PD, PN and PI processes. The GDA process model is formulated in general terms, facilitating adaptation to the majority of PI processes utilized in industry.
4.2 Factors influencing the design analysis task

It is important to recognize that the GDA process model primarily provides a sequence of phases to be followed in order to carry out design analysis tasks in terms of what to do and in which order, but offers very little support on how to do it. In order to be able to answer the question how to do it, a detailed insight into all aspects associated with the execution of the specific design analysis task is required. Such an insight is only achievable by considering the influence of both the endogenous and the exogenous factors. The factors elicited within PDA are those that have been deemed to have the most influence on the design analysis process. Factors are grouped along their levels of influence on the task: some appear within the design analysis basics (referred to as endogenous factors), some appear within the development project, some occur at the enterprise level, and some are outside the sphere of the enterprise, see Figure 4.4. The factors outside the design analysis basics are referred to as exogenous factors. The proposed classification has the advantage of indicating what leverage a stakeholder has upon such factors: the further from the design analysis basics, the more difficult it is to act upon them. Being aware of and appropriately handling the factors influencing the design analysis task should prevent fastidious iterations resulting from a poorly planned and organized design analysis task. In addition, understanding of uncertainty and potential error sources connected with these factors, together with techniques for handling them throughout the design analysis task, are important for providing insights to establish confidence in the decisions following the design analysis task outcome.
These factors affect the design analysis task more or less during all the activities carried out within a design analysis task. Furthermore, they have to be dealt with during the design analysis planning activity. First, it is important to notice that, although this is quite absent from the literature, many analysis activities are planned already from the PP as outlined in Figure 4.5 (upper picture). Such an early planning of design analysis tasks happens for example in cases where the product-to-be is already relatively detailed (incremental product development), when the enterprise has a detailed QA programme, etc.
This aspect is crucial, because during PP it is possible to act upon the factors at the enterprise level so that when the analysis starts these factors no longer act as constraints. The analysis task planning is then usually revisited (1’ in Figure 4.5) before task execution is initiated in order to agree on any adjustment relevant to the prepared task. When the analysis task planning directly precedes its execution (lower picture in Figure 4.5), it is no longer possible to act as widely at the enterprise level. It is e.g. risky to change the hardware system on such short notice, new software needs customisation and employees require training, etc. It is still possible, however, to act upon the project-related factors.

The factors at the environment level (regulations, standards…) must be dealt with, but can rarely be influenced during a development project. If the enterprise wants to influence them, they need to take lobbying actions or participate actively in the development of those regulations and standards.

4.3 Confidence appraisal activities (CAAs)

Confidence Appraisal Activities (CAAs) is the unifying term for a set of activities utilized within the PDA methodology with the purpose of ascertaining confidence in the predictions when performing a design analysis task utilizing the GDA process model. The CAAs involve activities of uncertainty and error handling, monitoring of the technical and task continuation progress, review and predictability assessment of established computational models and results as well as traceability and knowledge internalization of established data and information, as outlined in Figure 4.6. It should be noted that there exist many connections among the CAAs that make an unambiguous division hard to define. The compilation of various CAAs into the seven categories listed in Figure 4.6 is based on their purpose within the PDA methodology. Furthermore there are many links among the CAAs, the factors influencing the design analysis task, and the GDA process model followed to carry out the task. The factors affect not only the phases in the GDA process but also how CAAs are planned and carried out during the design analysis task. Some CAAs are more or less connected to only a few groups of factors or GDA phases. Other CAAs have a broader perspective and are therefore connected with multiple factors and/or activities within multiple design phases in varying degrees. These links are visualized in Figure 4.7 with the purpose of indicating the level, ranging from weak to strong, of connections between the confidence appraisal activities and the factors within the three phases of the GDA process model. These connections are further elaborated on within the following sub sections as well in the description of the sub activities carried out in the three phases of the PDA process model; see Section 4.4.
### Confidence appraisal activities

<table>
<thead>
<tr>
<th>Uncertainty handling in the clarification phase:</th>
<th>Uncertainty quantification in the computational model:</th>
<th>Progress monitoring:</th>
<th>Traceability:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Uncertainty and error source identification</td>
<td>• Characterizing</td>
<td>• Status and progress reporting</td>
<td>• Establishment of tracking system</td>
</tr>
<tr>
<td>• Uncertainty and error source categorization</td>
<td>• Aggregation</td>
<td>• Intermediate results communication</td>
<td>• Meta data extractions</td>
</tr>
<tr>
<td>• Uncertainty and error treatment</td>
<td>• Propagation</td>
<td>• Information &amp; feedback flow</td>
<td>• Continuous update of system</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Control and review:</th>
<th>Predictability assessment:</th>
<th>Knowledge internalization:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Task content assessment</td>
<td>• Validation activities</td>
<td>• Experience acquirement</td>
</tr>
<tr>
<td>• Self-checks and quality control</td>
<td>• Prediction capability</td>
<td>• Lessons learned documentation</td>
</tr>
<tr>
<td>• Verification activities</td>
<td>• Confidence scale assessment</td>
<td>• Knowledge transfer</td>
</tr>
</tbody>
</table>

### Factors

<table>
<thead>
<tr>
<th>Design analysis basics</th>
<th>Product development project</th>
<th>Developing enterprise</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Boxes" /></td>
<td><img src="image" alt="Boxes" /></td>
<td><img src="image" alt="Boxes" /></td>
<td><img src="image" alt="Boxes" /></td>
</tr>
</tbody>
</table>

Boxes represent phases 1 to 3 of the GDA process.

![Boxes](image)

Darker box fills indicate stronger connection.

### Confidence appraisal activities

Figure 4.6. Confidence appraisal activities.

Figure 4.7. Connections in CAAs, factors influencing the design analysis task and the phases of the GDA process.
4.3.1 Uncertainty handling in the clarification phase

The design analysis activities are greatly enriched when sources of uncertainties and potential errors among the factors associated with the current design analysis task are identified and handled. By recognizing and acting on, resources can be allocated adequately, analysis solutions can be scrutinized with appropriate approaches, and the interpretation and prediction based on the results can be enhanced.

Uncertainty handling during the clarification phase goes as follows: First, identification of uncertainty and error sources among the factors associated with the design analysis task is carried out. The identified uncertainties are then categorized based on their nature as being either aleatory or epistemic and the potential errors are categorized to be either acknowledged or unacknowledged. Once all sources of uncertainties and potential errors are identified and categorized, the uncertainties to be represented in the computational model and those that are not to be included are decided upon. Means of monitoring, reviewing and documenting uncertainties and potential error sources not included in the computational model must be established.

4.3.2 Uncertainty quantification in the computational model

Uncertainty quantification aims at determining how likely certain outcomes are, considering the uncertainties connected with the system studied. The uncertainty quantification involves first the selection of the appropriate approach for characterization of the inputs connected with uncertainties included and represented in the computational model. A selection of an approach should be done, and some of the often-utilized approaches are:

- **probabilistic model** e.g. stochastic randomness (primarily for aleatory uncertainties and ergodic systems)
- **non-probabilistic models** including evidence theory, possibility theory, fuzzy set theory
- **interval-based theory**
- **safety factor assignment**

The selection of an applicable approach within a given design analysis task is based on the available information such as experimental observations, theoretical arguments, and/or enterprise-stored knowledge. These have to be assessed to decide how to best represent the uncertainties in the computational model. It should however be noted that when selecting an approach, considerations of exogenous factors such as e.g.
time, resources (human knowledge, software capability and hardware capacity) and availability cannot be left out, since they could be in conflict with the best possible approach for characterizing and propagating the uncertainties.

Furthermore, the uncertainties could also be aggregated, if found to be adequate, into parameters utilized within the computational model.

Once characterization of the various uncertainties is completed they need to be properly propagated during the analysis with an adequate selection of methods for doing so. The selection of methods for uncertainty propagation depends on the representation chosen. Available approaches include:

- Monte Carlo (MC) simulation methods
- Taylor series approximations
- Statistical methods such as DOE and response surface methodologies (RSM)

The outcome of the uncertainty propagation generated is then investigated and evaluated towards the acceptance criteria for the predictions. This is carried out to quantify the confidence connected with uncertainties in the predictions made by e.g. ranking importance of the uncertainties based on the analyses results, or by quantifying uncertainties’ inference on the comparison between design analysis results with experimental outcome.

### 4.3.3 Progress monitoring

A well-planned progress monitoring activity for all activities of the design analysis task is important for consistent, efficient and adaptable integration of the design analysis activity within the product development project. Thus, any new or updated information applicable to an on-going design analysis task should be communicated among stakeholders involved, such as the engineering designer and project manager, in order to be able to use and provide most recent information, facilitating the possibility to act on and react as well as draw vital insights into the impact that it might have on the design analysis task. This also allows all stakeholders to make necessary assessments and mitigations, corrective actions or extensions to the ongoing engineering design activity as well as to any other project activities that are connected to or dependent on the current design analysis activity. Furthermore, if enterprise resources are modified at some stage of the design analysis task influencing or possibly altering the initial time and cost frames, this should be conveyed to the project management so that adequate actions can be taken as soon as possible. Such changes can originate from within the design analysis, but the more likely scenario is that it
originates from actions and decisions taken outside of the design analysis task and as well as outside the product development project. Similarly changes to or updates of environmental factors, such as new or updated standards, or changed capabilities in software and hardware utilized, need to be assessed as to whether it should be included in the design analysis task.

The information should be communicated through status and progress reporting on the on-going work, as outlined in Figure 4.8. This should be continuously prepared, communicated, reviewed and evaluated on a regular basis throughout the design analysis execution as well as the completion phases of the GDA process.

![Figure 4.8. Information flow within progress monitoring activities.](image)

The interval, format and layout should all be defined during the design analysis clarification and described in the task content brief. The information should generally provide the status of the on-going task to the stakeholders, such as project manager and engineering designer, with regards to technical and economic progress (spent time vs. actual progress), planned activities and expected milestones, as well as areas of concern that might call for updates of planning of not only the current activity but also other dependent or connected activities within the project. Furthermore, all known uncertainties, originally identified and handled as well as any newly encountered, that influence the task should be discussed during the review so that mitigating actions to the design analysis activity can be made. In this way deviations are caught early, and expensive, time-consuming iterations during the task execution phase, and irrelevant results, can be avoided.

### 4.3.4 Traceability

All models, data and information established during the analysis activities within the clarification, execution and completion phases should be gathered in some form of tracking system that could either be in an advanced form based on an engineering data management (EDM) system or based on a file system approach in which an
Excel file could be established in order to serve as the link between different sources and types of data (input data, modelling parameters, analysis output, results data), information utilized within the task (task foundation, assumptions made, results interpretations) as well as files produced (input, modelling, analysis, results, communication and report documentations) throughout the task. Various forms of meta-data, such as key input data and results obtained, can be extracted and stored in the system to aid in the tracking and identification of relevant data. Also, the responsible engineer for each input in the tracking system should be clearly identified, so that the source can easily be found if required.

Additionally, intermediate and final documentation should also be linked to the tracking system so that the content described in the documentation can be traced back to the correct source (results, analyses models, software used and in-house scripts). The stored data and information serves as the backbone for effective ways of finding potential alternative solution candidates within an on-going design analysis task, as well as when it has been completed, thus reducing the risk of the project and the enterprise resources ending up in situations where previous data cannot be found or re-created.

Furthermore, it allows for efficient scrutinizing and mitigations of intermediate results data in case changes in the development project affecting the design analysis activities occur that result in updated purposes and criteria on the activity.

Minutes of project and review meetings taking place during the execution and completion of the design analysis tasks are also important for the traceability of agreed actions and changes to the originally defined scope. The system should also allow for tracking of interfacing communications taking place relevant to the task so that the basis for actions taken during the analysis task can be traced back to decisions taken as a response to any raised query. Furthermore, the tracking system should include information on the control and review activities (see next section) so that any findings originating from these activities are also traceable.

In summary, using the tracking system allows for improved traceability in various generated data and information connected with the performed activities of the design analysis task in a systematic way, as well as connecting the reported outcome to the original scope. It also includes vital links between various changes to the scope due to decisions taken throughout the task. This will bring confidence to the task performed and predictions made, since the ambiguities of the final outcomes in relation to the scope are documented and traceable. Furthermore, it provides a foundation for confidence in future design analysis tasks that will be performed with the current task as basis.
4.3.5 Control and review

In the planning of a design analysis task, the goal of control and review activities is to ascertain that the task content brief includes all necessary information and that there is a balance among the factors influencing the task; that the assigned resources balance the time and cost frames; and that the requirement for predictability assessment is achievable with available information activities, to mention some examples.

The control and review activities within the execution and completion phases of the GDA process consist of self-check (SC) activities, performed by the analyst, and planned QC activities, performed by another team member with appropriate competence, in order to review and ascertain accuracy and correctness of the computational model as well as the results and documented interpretations of them under the given assumptions within the task content brief.

The QC activities can generally be considered as an iterative review loop in which the given remarks and comments on the work and responses to them are communicated back and forth between the analyst and the assigned resource for QC, as displayed in Figure 4.9, until mutual agreement and consensus are established regarding any concerns raised during the review. The outcome of the QC checks are important feedback to the project team since any relevant and required additions and modifications to the on-going task will be captured, updated and communicated at appropriate points in time of the task continuation. This will reduce the risk of providing irrelevant results as well as utilizing unnecessary time and resources.

![Figure 4.9. Information flow within control and review activities.](image)

Some of the control and review activities during the execution phase of the GDA process model are related to the verification part of the well-known methods of
verification and validation (V&V). Since verification is connected with mathematics and computational model accuracy it is placed under the control and review activities. Validation, on the other hand, is connected with physics and the possibility of the computational model to represent the real world, and is therefore within PDA placed in the predictability assessment activities, as is further discussed in Section 4.3.6. Expressed differently: verification ensures that the computational model has a certain quality, while validation gives info about the quality of the results.

Within PDA, verification is taken as the assessment of the accuracy of the computational model of the design solution. The verification is further divided up into code verification, focusing on determining that the computational model and solution options are accurately defined and that they are working correctly, and calculation verification, checking that each individual analysis result is accurate. These aspects are included as items in the SCs and the planned QCs. Also, a second opinion with regards to the quantification of uncertainties represented in the computational model should reduce the risk in the choices made. Additionally, these activities should reveal and capture any deficiencies connected with both acknowledged and unacknowledged errors in the established computational model, results and approaches used. In case the QC activity leads to required updates to the computational model, performed analysis or post-processing of the established results, it may be necessary to re-iterate one or more of the execution activities or even reassess the task description in the clarification phase.

The control and review activities in the completion phase should be performed with the objective to ascertain that the interpretations, validation (if decided to do it), and established documentation correctly reflect both the post-processing of analysis results and provide the adequate answer to the project query that it was initiated to investigate and provide insights on.

### 4.3.6 Predictability assessment

Validation within PDA looks for the degree to which the computational model is an accurate representation of the intended use of the model, and it is therefore addressed during the project completion phase in relation to the results interpretations. Figure 4.10, adapted from (Oberkampf, Trucano & Hirsch, 2004) presents the three domains connected with validation: analysis, validation and use. The analysis domain is the potential set of results data emanating from the computational model. The validation domain is the potential set of data from physical experiments, and the use domain is the potential parameter data settings from the working environment. Validation usually involves comparison of design analysis results data (in the analysis
domain) with data from physical experiments and tests (in the validation domain). Validation can also involve comparisons between the design analysis results data and physical measurement data from within operational environments (in the use domain). Figure 4.10a represents a situation in which a complete overlap of the use domain and the other two domains is present, making possible a complete validation of the use domain parameters. In situations with partial overlap, as shown in Figure 4.10b, not all parameter representations from the use domain are present in the other domains, and therefore they cannot be completely included in the validation matrix, that is, the data set emanating from the validation comparison of the various data.

Figure 4.10. Relationships between analysis, validation and use domains linked to validation activity, adapted from (Oberkampf, Trucano & Hirsch, 2004).

Figure 4.10c also shows that there are situations in which overlap of the three domains involved in validation does not exist. The comparison of the design analysis results data with physical measurements (from either validation and use domain) data are generally complicated, and the collection of data connected with design analysis and evidence (from either validation and use domain) for the comparison can be of varying degrees, from single-point values (showing trends) to advanced probabilistic models (describing distributions) as shown in the left picture in Figure 4.11, adapted from (Goh, Booker, & McMahon, 2005). Appropriate approaches for characterization of the computational performance parameters in the input as well as in evidence parameters connected with each comparison category (shown as letters A through F) are also included in the left picture in Figure 4.11.
The different categories of comparisons listed in Figure 4.11 are displayed and elaborated on in Figure 4.12, adapted from (Goh et al., 2005). In category A the analysis domain is represented by a single deterministic analysis result data that is to be compared to a single evidence data measurement from the validation domain that results in limited validation data. Category D on the other hand provides some more validation data since the analysis domain is based on interval value and the validation domain is based on range of values. This of course increases the knowledge of parameters and evidence to a moderate stage as shown in the confidence scale in the right picture in Figure 4.11. Most knowledge, and thus the highest confidence, is obtained when the comparison is carried out as a category F comparison where the analysis domain is based on a distribution function and the validation domain is based on statistical data. However, as indicated by the arrow going through the categories A, D and F, this increase in knowledge and confidence comes with a price in increased resource commitments.

This categorization facilitates the selection of and planning for an adequate approach for characterization of uncertainties within the computational model as well as the evidence collection requirement within the validation domain and the use domains to achieve a certain level of the confidence scale shown in the right picture in Figure 4.11. Furthermore, the relationships between the three domains involved in validation as shown in Figure 4.10b and Figure 4.10c emphasize the importance of
assessing the prediction capability of the established computational model, which within PDA is defined as:

Capability of a computational model to forecast the behavior of a product to-be in situations that the computational model has not been validated for.

<table>
<thead>
<tr>
<th>Category</th>
<th>Graphical representation</th>
<th>Category</th>
<th>Graphical representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td><img src="image1.png" alt="Graph" /></td>
<td>B</td>
<td><img src="image2.png" alt="Graph" /></td>
</tr>
<tr>
<td></td>
<td>(1,1) Deterministic analysis and validation with a single value.</td>
<td></td>
<td>(1,2) Deterministic analysis and validation with a range of values.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2,1) Analysis based on interval value and validation with a single value.</td>
</tr>
<tr>
<td>C</td>
<td><img src="image3.png" alt="Graph" /></td>
<td>D</td>
<td><img src="image4.png" alt="Graph" /></td>
</tr>
<tr>
<td></td>
<td>(1,3) Deterministic analysis and validation with statistical data.</td>
<td></td>
<td>(2,2) Analysis based on interval value and validation based on range of values.</td>
</tr>
<tr>
<td></td>
<td>(3,1) Analysis based on a distribution function and validation with a single value.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td><img src="image5.png" alt="Graph" /></td>
<td>F</td>
<td><img src="image6.png" alt="Graph" /></td>
</tr>
<tr>
<td></td>
<td>(2,3) Analysis based on interval value and validation based on statistical data.</td>
<td></td>
<td>(3,3) Analysis based on a distribution function and validation based on statistical data.</td>
</tr>
<tr>
<td></td>
<td>(3,2) Analysis based on a distribution function and validation with a range of values.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.12. Categories of comparison between data collection and evidence collection, adapted from (Goh et al., 2005).

The connection of prediction to validation within PDA is outlined in Figure 4.13, adapted from (Oberkampf et al., 2004b), in which the lower part of the picture is essentially an illustration of the validation, as discussed above, represented with a number of validation points. Here a validation point is taken as a denominator of a specific instance of analysis domain parameters and evidence parameters (from either
union of only analysis domain and validation domain or also including the use domain), which can be in the form of any of the categories outlined in Figure 4.12. The experimental outcomes of the validation points are compared to results emanating from the design analysis model. The comparison results in an inference based on the nature and magnitude of the identified differences.

Prediction points as shown in Figure 4.13 are the denomination for certain representation of the use domain parameters, which can also be in the form of any categories outlined in Figure 4.12. The upper part of Figure 4.13 is related to prediction, and the top arrow from one of the shown prediction points in the use domain to the computational model implies that the requested characteristics of the results to be predicted by the computational model could extend beyond the information available among the current established validation points. The confidence in the predictions (top right parallel trapeze in Figure 4.13) is connected to the inference from the comparisons of the validation points with the position of the prediction point determined by the computational model results. The inference from validation comparison is considered in the predictions as an additional predictive uncertainty (Roy & Oberkampf, 2011).

In situations with complete overlap of the three domains, see Figure 4.10a, the prediction can be said to be an interpolation or, put differently, a retrodiction of already established and available results. This is consequently denoted as requiring a low (or limited) necessity for prediction capability since no extrapolations of results is necessary. A similar scenario exists when the validation and prediction points are positioned as shown in Figure 4.14, left.

Figure 4.13. Relationship between validation and prediction, adapted from (Oberkampf et al., 2004b)
Figure 4.14. Two situations requiring different prediction capability.

On the other hand, in situations where the prediction point is outside both the analysis domain and the validation domain, as shown in the right picture in Figure 4.14 the necessity for and requirement on prediction capability is high. This is also the case in situations with no overlaps in the three domains; see Figure 4.10c, in which the computational model is to be used for predictions that are completely outside both the validation and analysis domains. Typical situations requiring high prediction capability are products to be used in environments that can be categorized as non-ergodic processes or in which the test specimen differs from final product operating in the use domain.

With the relationship between validation and prediction in place, the level of confidence in the predictions can be represented as a confidence scale as outlined in the right picture in Figure 4.11, adapted from (Goh et al., 2005). Increased level of data and evidence collection results in increased knowledge, allowing for improved confidence in the prediction. However, it should be noted that with the increased confidence comes increased resource commitment, which is important to take into account when defining and planning for the requested confidence level for certain design analysis tasks. Techniques such as Phenomena Identification and Ranking Table (PIRT) are helpful to efficiently plan the validation activities (Oberkampf, 2004b). Furthermore, handling of all relevant uncertainties and potential error sources as well as accuracy assessment in all three domains, not only in the analysis domain, needs to be systematically managed within the design analysis task to facilitate high prediction capability.

4.3.7 Knowledge internalization

Documentation and internalization of acquired experiences and lessons learned from the design analysis task is important. The established data and information elicited
should continuously, as well as at the end of the project, as far as practically and economically possible, be elicited, formulated and stored and handled within the enterprise in a systematic manner that facilitates decision support for future product development projects and product generations. It should allow for inclusion in the enterprise’s core knowledge system, such as QA framework and established guidelines, and it should be formulated in such a way that potential improvements in current practices and tools will become available not only for the project members but for the enterprise as a whole. This will serve as the foundation for confidence appraisal in later design analysis tasks in the same project as well as in other projects within the enterprise. It also serves as the basis for assessment of required changes of the available competence and possibly even organizational aspects in order to perform future design analysis tasks.

The stored data, information and knowledge can also be utilized in the establishment of design support tools such as knowledge-based engineering (KBE) systems as outlined in (Ahsan & Shah, 2006). The systems could be established as advanced tools, such as artificial intelligence expert systems, or be based on case-based reasoning as well as more straightforward approaches such as design catalogues and tools and procedures that are all developed with the purpose of aiding the user with information from previously deduced knowledge to the question under study. A case-based system can typically be based on an implementation into a spreadsheet or database domain model where previous development data are stored and the users extract requested data by comparing the proposed model with similar design in the domain model, see e.g. (Waheed & Adeli, 2005).
4.4 Activities within the three phases of the GDA process model

The activities connected with the three phases of the GDA process model as well as the CAAs are outlined in the following sections.

4.4.1 Analysis task clarification activities

There are several possible origins for the initiation of a design analysis task, which can be driven by evaluations of product specifications or by proposals for re-design of a product. The design analysis task can also originate from previous or ongoing activities: project team members identify the need for deeper, extended or additional analysis activities investigating further aspects of the product-to-be. In this latter case, it is also important to go through the identification of the task activities, although less thoroughly, to assess the relevance of the task and to get approval for further preparation and planning of the task.

Discussions take place with the different stakeholders involved, usually the project manager, the departments responsible for engineering design and design analysis, and possibly also an EC enterprise – given that the EC enterprise has already been approached with the purpose of assessing the relevance of a potential design analysis task. In these discussions the factors influencing the task and sources of uncertainty and potential errors connected with them are elaborated upon. A pre-study is often performed within the identification of the task (activity 1a in Figure 4.15), providing further insights into the task relevance as well as a foundation for the discussions of the factors influencing the design analysis task, e.g. effects of different choices of appropriate software and hardware resources, expected requirements on input and outputs, anticipated resource demands and available cost and duration to perform the task. A preliminary mission statement is written as an output from the identification activity, as displayed in Figure 4.15, in which the relevance of the task is emphasized together with the description of how the analysis results will be used and integrated within the project. The mission statement forms the basis for, and can significantly affect, the decision whether or not to continue planning the task.
In order to assure that the task content brief (activity 1b) will be comprehensive, depicting the task purpose and taking into account the standpoints from the various stakeholders, it should cover required inputs, expected outputs considering the factors influencing the task as well as elaborations on modalities of CAAs to be carried out. The deliverables, which can be in the form of raw data points, or in the form of more elaborated interpretation and conclusion of the performed activity, must be carefully...
specified. Without this proper description, the information delivered during the execution and the completion of the task might be inconclusive. Furthermore, the validation activities in connection with requested confidence level should be given attention and planned since they are time-consuming and costly, involving resources outside the design analysis task. Moreover, as prototypes are made throughout the project continuation, synergies could be found between both analysts and engineering designers facilitating improved means for reviews. The task content brief should be outlined so that all stakeholders have clear notion on how the listed items in the content brief are to be handled during the task execution and completion phases. The analysis-specific knowledge and expertise are not always apparent to other stakeholders in the project and should thus be provided throughout the planning of the task. This means that, in general, the brief will not be complete or even correct unless the analysts are given the opportunity to comment on it, and the project manager, the engineering designers and other project team members need to be open for discussion. It can be important to also include explanation of the working principle of the product to-be and its environment, so that the analysts get a better and wider understanding of the problem to solve and where the current task fits into the whole development project. The task content brief should, as a minimum, include statements on the outlined in Figure 4.16.

Once all items in the brief are in place, the analysis activity should be carefully planned and a formal document should be prepared and mutually agreed on between the analyst and the project leader that forms the basis for the analysis execution (activity 1c). Often this involves negotiation among the various stakeholders due to the simple fact that constraints in terms of resources, knowledge and time all affect what can be achieved in the assessment of the specifications under evaluation. If agreements made violate the description in the task content brief, or further clarifications are found to be relevant, then it should be updated. In case the parties cannot agree, it may be necessary to re-iterate activities 1b and 1c or even 1a.

All the above are vital to avoid having the execution activity initiated with unclear understanding of the risks and of the expected outcome of the task. It is furthermore very important not to proceed further without mutual agreement, and a firm decision to continue as well as a proper description of agreed monitoring activities, intermediate milestones and review activities, since this will introduce additional uncertainties and problems that might endanger not only the success of the design analysis activity but also the complete project realization.
Figure 4.16. Minimum list of items to be included in the task content brief.

<table>
<thead>
<tr>
<th>Items connected with the identified factors influencing the design analysis task:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Items associated with the design analysis basics:</strong></td>
</tr>
<tr>
<td>• Theoretical foundation and representation of the system to be analysed.</td>
</tr>
<tr>
<td>• Basic computational model information such as data concerning material, load and boundary conditions.</td>
</tr>
<tr>
<td>• Outline of modelling aspects and programming approach when establishing the computational model.</td>
</tr>
<tr>
<td><strong>Items associated with the product development project:</strong></td>
</tr>
<tr>
<td>• Purpose and the scope of the task.</td>
</tr>
<tr>
<td>• Description of all relevant product specifications to be investigated.</td>
</tr>
<tr>
<td>• What level of concretization in established computational models and extracted results are expected.</td>
</tr>
<tr>
<td>• Form and extent of the intermediate and final deliverables.</td>
</tr>
<tr>
<td>• Integration of the results into the development project.</td>
</tr>
<tr>
<td><strong>Items associated with the developing enterprise:</strong></td>
</tr>
<tr>
<td>• Elaborations on guidelines, procedures and QA framework that are available as support when performing the task.</td>
</tr>
<tr>
<td>• Hardware and software as well as the configuration of those available to accomplish the task.</td>
</tr>
<tr>
<td>• Human resources and competences available to carry out the task.</td>
</tr>
<tr>
<td><strong>Items associated with the environment:</strong></td>
</tr>
<tr>
<td>• Standards and regulations the task should comply with.</td>
</tr>
</tbody>
</table>

**Modalities of confidence appraisal:**

• **Uncertainty handling outside computational model:** Establishment of means of monitoring, reviewing and documenting uncertainties and potential error sources not included in the Computational model.

• **Uncertainty quantification in computational model:** Determination of the subsequent activities of uncertainty quantification for identified and selected uncertainties to be included in the computational model.

• **Progress monitoring:** Outline of the interval, format and layout of status and progress monitoring activities.

• **Traceability:** Determination of the requested level and format of traceability of the data and information connected with the performed activities.

• **Review:** Determination of the type, level and extent of review activities. Statement on the QC activities that are to be performed by the analyst and on the corresponding QC activities to be performed.

• **Predictability assessment:** Description of the validation activities to carry out. Determination of the required prediction capability and confidence level the current task should result in.

• **Knowledge internalization:** Determination of how and to what extent the generated data and information should be capitalized outside project documentation.
4.4.2 Analysis task execution activities

The model creation within pre-processing (activity 2a), see Figure 4.17, involves many aspects starting from compiling the task content brief with the purpose of understanding and identifying the physics of the problem, followed by establishing a mathematical model. The theoretical foundation is here not confined to the adaptation of the fundamental laws of nature, originating from biology, chemistry or physics, but also involves the technical constraints emanating from areas like materials science, manufacturing techniques etc. The next activity is to define a representative engineering model (such as a geometrical model or a functional model) that forms the basis for establishing the computational design analysis model. Part of or even the whole engineering model is in some cases established outside the analysis activity by the engineering designer.

With the engineering model as the basis, the computational model is established, including relevant items listed and deduced from the task content brief. Main focus is obviously on the items connected with the endogenous factors. Material properties, idealizations (i.e. beams and shells in FEM), discretization (i.e. mesh density in FEM), cell density in CFD, initial and boundary conditions and loading are among the factors always connected to a design analysis activity. Furthermore it is important that the computational model is established with the given constraints that exogenous factors impose on the design analysis task. The uncertainties selected within the task clarification phase for representation in the computational model should be characterized and aggregated in the pre-processing of the computational model. The approach for propagation of uncertainties itself should be determined. The traceability system should also be set up, if not already available during the design analysis clarification phase, and then continuously updated throughout the design analysis task continuation in order to provide traceability of all analysis activities involving inputs, established models and results, data and information extracted during the task as well as in the outgoing documentation.

The approach and settings applicable for the solution processing (activity 2b) activity should initially be defined, followed by scrutinizing the adequate number of results needed to produce the required number of result instances. Furthermore the approach for uncertainty propagation puts constraints on, yet also reveals the opportunities for, what type and number of results can be extracted. The method chosen should of course enable extracting the required results.
Figure 4.17. Defined sub activities within the design analysis task execution phase.

The analysis task needs to be executed in a way that allows for intermediate results, analysis status and areas of concerns to be communicated to all relevant stakeholders within the project and enterprise. Changes agreed upon during the project status meetings must, of course, also be included in an updated version of the task content brief, which should at all times contain the most up-to-date agreed description of an on-going task. If the severity and impact of these are of such nature that the current design analyses task has to be re-planned, the execution phase activities of the current
task should be put on hold and the task clarification phase reinitiated. In order to ascertain accuracy and correctness of the established computational model together with intermediate as well as final results there should be SCs and planned QC activities involving both types of verification: initial code verification to assess the computational model and calculation verification to assess the intermediate results produced. Furthermore, all analysis activities should be tracked in the analyses traceability system. The information flow within progress monitoring, review and traceability activities is displayed in Figure 4.18.

The results obtained are assessed by listing raw output data, displaying contour plots, and animation of results within the post-processing activity (activity 2c). This should be done to make judgements and provide understanding of the general model behaviour, to the extent that calculation verification of model accuracy and convergence in the established results can be performed. The listing should consist of output information from solution processing, such as error and warning messages along with the analysis results of interest. Studying the reactions from the system and comparing them to applied loads is one part of the accuracy assessment. Any discontinuity at locations where they are not expected to be is a sign of inadequate accuracy, and improvement in discretization might be needed. Unexpected and irrelevant occurrences of high local results should be viewed and judged as real or spurious. All of the above are part of the SCs to be performed by the analysts.
Planned QC activities of the established results are also carried out to confirm the findings of the SCs including investigation and evaluation of the propagated uncertainties as well as assessing the unacknowledged errors overlooked by the analyst during the execution activities. When a consensus and mutual agreement are reached on the computational model, the analyses performed, and the results extracted and post-processed, the design analysis task can be considered to be verified and the results can be used in the completion phase activities.

4.4.3 Analysis task completion activities

The results interpretation (activity 3a) relates to the interpretation by the analyst of all relevant data and information that can be drawn from the analysis task execution. Whenever performing a design analysis, the established outcome needs to be interpreted, documented and presented in a way that facilitates decision making on an overall level throughout the engineering design process. How the established design analysis data should be transferred into descriptive product development information of the product-to-be is part of this activity. Only communicating the raw output data from the design analysis results (data listings and fringe plots for example) to decision makers largely misses the potential of a design analysis task. Communicating the full set of interpreted and evaluated results together with conclusions reached on how to incorporate the results in the project is much more valuable and provides greater insights into the problem addressed. Figure 4.19 outlines all sub activities of the analysis completion phase as well as the confidence appraisal activities connected with it. Predictability assessment of the model results is also connected to the results interpretation activity (activity 3a); see Figure 4.19. Based on the outcome of these activities and the verification activities carried out, the confidence level should be assessed in order to ascertain that the requested level is actually fulfilled within the task under the given assumptions.

In documentation and communication (activity 3b), the extracted data, information and conclusions drawn are documented and communicated, primarily at the project level, but also to other stakeholders. Additional improvement proposals should also be prepared and documented for making accurate conclusions and decisions, within the project, on the effect on the product studied. In integration of the results into the project (activity 3c), the output is integrated back into the development project, and the results are taken up in the project decision procedures. The output forms the basis for possible further analyses.

The results of uncertainty quantification in the computational model during task execution should be further elaborated on so that they can be clearly expressed in the
task documentation in such a way that it adds value to the performed task. Furthermore, this should be communicated to the project management and other relevant stakeholders so that proper decisions within the engineering design process can be taken. This includes all sources of uncertainties connected with the factors influencing the task that are selected to be handled within the design analysis task. Uncertainties connected with the physical test environment within the validation domain should also be addressed similarly as the uncertainties connected with the design analysis are treated in the previous phases. There are usually many aspects to consider, including for example the accuracy of the measuring system, the approach to enforcing loading and constraints, properties of the tested object (prototype of the product-to-be) just to mention a few. The findings in the QC of the conclusions drawn in the results interpretation, and the predictability assessment activities during the interpretation activity should also be used to provide the project team with feedback on the confidence level of the work performed and conclusions drawn from it. The established documentation should also be checked for conformity (by both the analyst and the resource responsible for QC) to the defined purpose in the content brief, and to ascertain that all findings and conclusions in previous sub activities are correctly reproduced within the documentation. The final documentation should be communicated to all stakeholders of the current project in agreed appropriate channels and formats for decisions on subsequent actions, allowing for integration in the project (activity 3c).

At the end of the project, another aspect of importance is that of capitalising the knowledge and experience acquired during the project. The experiences gained and lessons learned through all design analysis activities should as far as practically and economically possible be elicited, formulated and stored as enterprise core competence for use in future projects (knowledge internalization).
Figure 4.19. Defined sub activities within the analysis task completion phase.
4.5 Summary of the elements of the PDA methodology

Here the constitutive parts, previously accounted for, are linked together into an illustrated overview of the PDA methodology – in Figure 4.20.

![Diagram of PDA methodology and CAAs](image)

**Factors influencing the GDA process model and the CAAs**

- **A. Design analysis basics**
  1. Material
  2. Loads
  3. Boundary and initial conditions
  4. Modelling
  5. Discretisation
  6. Programming

- **B. Product development project**
  1. Specifications
  2. Purpose
  3. Level of concretisation
  4. Time
  5. Costs
  6. Process monitoring

- **C. Developing enterprise**
  1. Hardware
  2. Software
  3. Quality assurance framework
  4. Organisation
  5. Employee competence
  6. Procedures & enterprise-stored knowledge

- **D. Environment**
  1. Legal regulations
  2. Environmental regulations
  3. Hardware suppliers
  4. Software suppliers
  5. Customer standards
  6. Industry standards
  7. Certifying standards

Figure 4.20. Overall outline of the elements that together form the PDA methodology.
5 Conclusion and future research

The conclusion is presented in Section 5.1, followed by recommendations for future research in Section 5.2.

5.1 Conclusion

The MAIN RESEARCH OBJECTIVE set out for the research project was formulated as follows:

To outline the fundamentals of a methodology for predictive design analysis, a computer-based design analysis methodology allowing for increased confidence in the predictions resulting from the design analysis activities regarding the critical design parameters and their influence on the behavior of the product-to-be (artifact) throughout the entire design and development of the artifact.

The PDA methodology is built upon three originally developed constitutive parts: the GDA process model, factors (endogenous and exogenous) and the CAAs. The PDA methodology outlines how the GDA process model activities within the phases of the process model are influenced by factors emanating from the environment in which the design analysis task is executed. Furthermore, the CAAs are established in order to ascertain the confidence in the predictions made during the continuation of the design analysis task. This allows for an increase in the confidence in the design analysis process as well as in the results provided as input to other ED activities within the development project.

The GDA process model is formulated in general terms, facilitating integration and adaptation to the majority of engineering design processes utilized in industry and it provides, at an operational level, an overall approach to planning and execution of design analysis tasks as well as for monitoring, communicating and incorporating the obtained findings into the engineering design project - from which the design analysis task is originally derived. Research in methods and approaches to establish the computational model, scrutinizing the solutions as well as post-processing the results, is not considered explicitly in the current thesis. It is however built upon well-established and well-known research work within the design analysis basics topic. By
the introduction of the factors influencing the design analysis task, it is possible to define requirements for how the execution of the analysis task should be carried out to satisfy the agreed purpose and scope. It has been shown that it is important to consider the influence of both the endogenous and the exogenous factors in order to achieve a holistic view on the design analysis process. The CAAs provide a foundation for ascertaining confidence in the predictions when performing a design analysis task utilizing the GDA process model under the influence of the identified factors. In industry the activities of model correlation, calibration and updating during validation are often performed as a part of the predictability assessment. However the decision to undertake these activities should be considered with care and with the purpose of understanding the differences identified during validation comparison and not of finding model parameters resulting in fewer differences. It is instead important to consider and present the predictive uncertainty stemming from the validation comparison to the decision makers so that this uncertainty is not underestimated in the forthcoming predictions.

The PDA methodology presented proposes a large array of recommendations and activities that can seem overwhelming at first but are necessary for large development projects. In really large projects, or if the design analysis task involves multiple resources, it could be beneficial to appoint a dedicated resource for handling the interfacing/integration of the design analysis activities with other engineering activities in the project in order to assist the project manager in planning, monitoring and prioritizing the design analysis activities. This resource could be referred to as a technical supervisor. Another important role for the technical supervisor is to support the analysts in seeking the overall status and knowledge of the project in general and how it links to the specific task activities being performed. The technical supervisor could also assist in the interfacing between the individual engineers and analysts, providing an overall perspective on their interaction.

Although the PDA methodology is primarily developed with large and complex projects in mind, it can also be very useful as a guide for performing smaller, less complex projects, but an additional number of elements need to be taken into account, such as trade-offs between costs and efforts, competence availability, or validation capabilities. Even if design analysis within this thesis is primarily considered in terms of mechanical working principles, the open-ended structure of the PDA methodology allows for its utilization in other disciplines of CAE analyses such as electromagnetism and fluid mechanics. Furthermore, it can be applied in situations where single physics are considered as well as in situations where integrated multi-physics are to be studied, which are planned, executed and completed in close connection to each other.
It has been shown that elements of the PDA methodology, at an operational level, facilitate closer cooperation between engineering designers and analysts and thus likewise improved understanding between the two categories of specialists. The constituent GDA process model has furthermore been shown to provide 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 has also been shown to be successfully applied for some alternative design analysis tasks, such as explorative and optimization studies, evaluation, support for physical testing, and method development, demonstrating the adaptability of the methodology for various purposes of the design analysis tasks.

5.2 Future research

It should be noted that thorough evaluation of the established methodology has not been conducted, although elements of the PDA methodology have been shown to be feasible and applicable by the papers presented. It would be interesting to perform an evaluation of the established PDA methodology that systematically takes into account elements important for the assessment of a methodology, beyond effectiveness and efficiency. Continued research on the application of the PDA methodology to some selected product development process models would strengthen the methodology by identifying additional aspects relevant for future versions. For instance it can be of interest to study the influence of aspects of enterprise organizational nature as well as on the personal knowledge level in line with the “Professional Simulation Engineer” program developed by NAFEMS (2014).

Furthermore it would be interesting to investigate what adaptations of the PDA methodology are applicable and required when other identified situations from a product life cycle perspective are to be considered. One such situation could be to apply the methodology to projects during the use phase rather than the development process, in which analysis purposes could be to perform e.g. life extensions, or failure scenario investigations. Further development of the methodology with emphasis on project size, product complexity as well as enterprise size could also be interesting for identifying elements and factors to be considered to allow for an efficient utilization of the PDA methodology also for various environments in which it will be used. Further research into the aspects of process integration of PDA to the product development process as well as research on implementation of a database system to
facilitate the handling of the integrated workflows will also contribute in this area. Handling the workflows, also including those within the engineering design process will 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 analyze specific parts of the workflow such as: bottlenecks, abnormal costs for specific activities, hardware and software problems and opportunities etc.

Investigation of adequate adjustments to the PDA methodology applied to other design analysis disciplines such as electromagnetic and fluid flow as well as multidisciplinary problems such as fluid structure interaction (FSI) would contribute to an even broader foundation for the methodology. Further research connected with the CAAs is regarded as an important field of future research, since the confidence in the prediction capability is closely related. Two paths are envisioned, one in which in-depth research is carried out within the identified activities to deepen the understanding in certain areas. Another potential approach is to continuously follow, monitor and extract research findings performed by others in a slightly broader perspective in order to adapt these findings to the PDA methodology. A few potential areas are listed below:

- Contributions to the further development of currently available methods for uncertainty handling as well as approaches for uncertainty quantification within the computational model.
- Research connected with e.g. formats, channels, and level of details connected with progress monitoring aiming at facilitating improved understanding and thus building trust among stakeholders involved in the design analysis task.
- Investigating ways for improved traceability functionalities and capabilities by e.g. studying enhanced EDM systems.
- Identification and contribution to the research focusing on control and review connected with the computational model in order to suggest further important aspects for an efficient implementation while at the same time assuring high confidence in the activities.
- Continued efforts on knowledge internalization, which provides vital insights for future design analysis tasks if planned, documented and stored in a way that allows for easy and fast retrieval when the information is requested and provides the basis for enterprise knowledge enhancements.
- Further in-depth research on predictability assessment involving both aspects of validation and approaches to prediction capability assessment. By continuing to build upon the current representation of these aspects with the current PDA methodology should provide the engineering designer or
analyst, whoever is performing the analysis, with tools and guides valuable when taking on further responsibility. Furthermore it will also give other stakeholders insight into what can be expected and what will be required to achieve a given confidence level in prediction, which is an important aspect in order to get approval and endorsement from management.
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Appended papers
Efficient use of finite element analysis in early design phases

Eriksson, M.


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EFFICIENT USE OF FINITE ELEMENT ANALYSIS IN EARLY DESIGN PHASES

Martin Eriksson
Lund University, Lund Institute of Technology
Division of Machine Design, Department of Design Sciences,
P.O. Box 118,
Lund, SE- 221 00
Sweden
telephone: +46 46 222 85 11, fax: +46 46 222 46 16, email: martin.eriksson@mkon.lth.se

ABSTRACT
The utilization of analytical/numerical techniques and methodologies within product development and design is seldom discussed in the literature. This leads to a loss of a holistic perspective on product development and design. The exclusion of analysis methods and techniques implies that their impact on the development/design procedures is considered negligible and is not regarded as a constituent part in the establishment of a generic product development procedure model.

The overall focus of the work presented in this paper has been to show how extensions and adaptations of available techniques can be introduced in the mechanical engineering design process, or design process for short, to promote the general holistic perspective of product development. The example presented emphasizes the value of combining Design of Experiments (DOE) and Finite Element (FE) analysis into an effective tool to be used in the early phases of the design process to predict, at least to some extent, the final behavior of the product-to-be.

Keywords: Conceptual Design Phase, Finite Element Analysis, WWW-based Design Tool and Design of Experiments.

INTRODUCTION
In a historical perspective there has always been a search for establishing theoretically consistent algorithms and notations to fulfill the growing need for analysis. In addition, mechanical aids have also been developed to solve not only intellectual problems but also physical problems emerging from everyday life.

With the industrial revolution the manufacturing of products shifted from handicrafts to mass production, which characterizes industrial production. At the turn of the 20th century a stable industry structure had evolved, though complex products were still developed facing numerous uncertainties. To ensure high quality and reliability, all products had to be adjusted individually in order to work properly. The adjustments were generally not performed in any organized way with respect to possible sources of error, and thus led to uncertain and even uncontrollable time and costs estimations. A better way to deal with this would be to use a systematic approach to handle the frequently occurring problems.

Shewhart and Tippet, as mentioned by Bisgaard (1991), introduced systematic approaches to deal with these problems in the 1920s and 1930s. They based their approaches on the idea of Design of Experiments (DOE), which shift from the traditional one-factor-at-a-time experiments, where only one variable is altered at a time, to planned approaches where all variables are altered simultaneously in a systematic way. DOE has the important possibility of finding the overall best values that could not be detected with the traditional one-factor-at-a-time experiments because interactions among the studied variables could not be evaluated.

With the works of Deming (1986) and Juran (1962), the idea of quality was introduced to Japanese industry, which adopted the concept of active quality control within product development. This was later further developed and elaborated by the Japanese Professor Taguchi (1993), who established an approach to quality that is frequently used in industry all over the world today.
The approach of Predictive Design Analysis (PDA) provides the engineering designer with tools to use design analysis more effectively in all phases of the design process. The use of PDA will allow the engineering designer to evaluate some of the criteria in the conceptual design phase using a quantitative approach, thus providing a higher probability of success in the subsequent decision making procedure. PDA is a subconcept of Predictive Engineering (PE) which focuses on the establishment of prediction of product features throughout the whole design process.

**NOMENCLATURE**

- $\mu$ = mean value of the normal distribution.
- $\sigma$ = standard deviation of the normal distribution.

**OBJECTIVE**

The objective established for the work presented in this paper has been to combine design analysis methods with statistical methods in order to give the engineering designer or analyst (hereafter referred to as designer) an efficient tool to be used at all levels of abstraction in the design process. The applicability of DOE within PDA is discussed. Further, the implementation and utilization of DOE together with PDA in the design process is described with an example. In the example, the DOE is based on a 2-level factorial approach, and Finite Element (FE) analysis is used to exemplify design analysis.

**PRODUCT DEVELOPMENT**

The development of products is today treated in a systematic manner, where the goal is to efficiently and effectively develop products of high quality. The product requirements established are translated into technical criteria that are used to evaluate different candidate solutions.

Several names and definitions have been associated with the work of developing product development processes over the years, and these processes have been interpreted differently by different people. Examples of expressions used are Integrated Product Development, Concurrent Engineering, and Simultaneous Engineering and a buzzword commonly connected with all these approaches is conceptual design. Although there are differences in names, the approaches are generally easy to deduce and they all have a similarity in focusing on the fulfillment of a need that initiated the development activity. Another important feature shared by the approaches is that the development of a product is organized and performed systematically. The differences between various procedure models for product development lie partly in how many functions within a company are included in the model (marketing/sales, design, production, and management/financing). The approach of Pahl and Beitz (1996) documented in *Engineering Design - A Systematic Approach* is one of the most utilized and is adapted in this work to exemplify the design process. The approach is product oriented and focuses on the product-to-be, and their schematic description of the general design process can be seen in Fig. 1.

![Figure 1: Approach to product development adapted from Pahl and Beitz.](image)

The starting point of the majority of all approaches to product development is the establishment of criteria that must be fulfilled in order to satisfy the user requirements on which the criteria are based. In the conceptual design phase, the objective is to generate different working principles, and combinations of those, which solve the overall function. The main activity in conceptual design can be characterized as synthesis. The concepts are then evaluated against the criteria that are mainly qualitatively oriented.

After the conceptual design phase, the resulting concepts have to be finalized in the subsequent design phases. The process of developing the final design involves several iterations of synthesis, analysis, evaluation and decision making, where the total cost of the project increases as the number of iterations increases. In these latter phases of the development process, analysis is today mainly utilized for verification purposes only. The main objective of analysis is to assist designers in their work of simulating the behavior of the product-to-be as a basis for the subsequent decision making process, i.e. selection of "best" candidate solution.
PREDICTIVE DESIGN ANALYSIS

Analysis is not currently regarded as a main component in the establishment of a generic product development procedure model. In order to overcome this shortcoming, analysis should not be treated only as a verification tool to be used in the latter stages of the design process. It should rather be seen as an effective tool to be used in the establishment of the foundation for the prediction of the final behavior of the product-to-be and thus broaden the basis for the decision making process. By using the proposed approach of PDA, the designer will be able to evaluate some of the criteria in the conceptual design phase using a quantitative approach, thus improving the probability of the subsequent decision making process. Based on the problem specification, different physical and mathematical quantities can easily be evaluated with PDA. The result of PDA can then be evaluated further along with the remainder of the qualitative criteria by some well-known evaluation technique, see e.g. Ullman (1997), where the purpose is to sort out those concepts that are most promising and worth looking into in more detail. The most significant advantage of applying design analysis early in the design process is the shift from verification to predictive analysis. Bjärnemo and Burman (1999) established the following objective for the PDA approach:

“Development of computer based tools for generating features of the product-to-be that are computationally obtainable on all levels of concretization throughout the design process.”

To broaden the use of design analysis also at the earlier stages of the design process, the PDA approach is very powerful in the way that it extracts the few vital variables from the many trivial ones. These vital variables can, if necessary, be studied further, e.g. in an optimization analysis, where the optimum variable setting found in PDA works as a good starting variable configuration. The sensitivity of a product design to environmental factors can also be analyzed by the approach described. Interactions between design variables and environmental variables might also be included in the study. In design for manufacture, the uncertainty in design dimension related to different manufacturing processes can be evaluated with PDA.

The essential part of the PDA approach is design analysis, which can be divided into a number of topics depending on the nature and/or the purpose of the analysis, e.g. Multi Body Simulations (MBS), Computational Fluid Dynamics (CFD), magnetic and electrical field analysis, and structural and thermal analysis. To include all areas is beyond the scope of the work published in this work, but the general point of view presented here applies to all topics with only minor changes. Structural analysis is chosen to represent design analysis since it is one of those most frequently used design analysis tools in the design process.

In the holistic perspective of product development it is also essential to enhance the view of the traditional deterministic analysis methodology to the more general view of the stochastic methodology. The deterministic approach discounts variability in investigated variables and thus ignores the possibility of failure; see Fig. 2. Safety factors are introduced that, to some extent, recognize the existence of uncertainties. In the stochastic approach the uncertainties are accounted for, and the resulting response can be directly compared with given specifications. One of the areas most utilized within the design process is robust design, where distributions of loading are compared to the material strength distribution. The objective of robust design is to make products robust to environmental conditions and insensitive to component variations. Another area where statistical methods are often used is in the gathering and establishing of material properties. These data are often given in textbooks in the form of mean values of some distribution. Other areas where the theories have been used are the study of fatigue data, in studies of reliability and quality, and in the selection of load cases, i.e. magnitudes and directions that are often based on some load spectrum.

![Figure 2: Statistical representation of a studied variable](image)

Although the use of stochastic methodologies will most certainly lead to development of more reliable products, many issues of uncertainties still emerge during the design analysis. Marczzyk (1999) has made a categorization of possible uncertainties that will become visible when performing analysis, which separates the uncertainties into two major areas, physical uncertainties and numerical simulation uncertainties. The first category contains load and boundary conditions, material and geometry problems. The latter category focuses on the implementations of numerical methods when problems arise in modeling, mathematical and discretization uncertainties, bugs and programming errors and numerical solution uncertainties (round off, convergence criteria). The example presented in this work will address some of the first mentioned sources of uncertainties while utilizing DOE to organize a set of FE analyses. The general idea of DOE is to perform as few analyses as possible, without compromising accuracy, to obtain a high-quality solution. DOE is based on fractional factorial experiments, which are arrays that alter the studied design variables at different levels systematically.
Depending on the choice of design variables, different kinds of responses (studied results) can be produced, e.g. stresses, displacements, design layouts, or working principles. Statistical evaluation methods are then used to extract vital information from DOE and also to organize and visualize it. The sensitivity of a product design to environmental factors can also be analyzed with DOE. Interactions between design variables and environmental variables might also be included in the study. The combination of DOE and FE analysis gives the design engineer a powerful analysis tool to evaluate the product, along with other engineering tools, at all phases of the design process.

The use of DOE today can clearly be divided into two major groups depending on the basic approaches. The first group is based on the approach of Taguchi (1993). In this approach it is preferred to consider design variables at three levels, and the evaluation of the experimental results is made of signal to noise ratios (S/N-ratios). In practice three S/N-ratios, called smaller-is-better, larger-is-better and nominal-is-best are used to handle most situations. Over the years there has been a lot of discussion regarding the efficiency and accuracy of the Taguchi method among western statisticians, see e.g. Box et al. (1988). They prefer to use an approach called two-level experiments where the design variables are treated on two levels. The implementation presented below has support for both these approaches.

WWW CLIENT/SERVER IMPLEMENTATION

Ever since the development of the transistor the speed and efficiency of computers have increased. Subsequent research has resulted in smaller and faster computers. Along with the improvement of computers, their communication has been enhanced. Under the leadership of the United States Department of Defense's Advanced Research Project Agency (DARPA), ARPANET grew from a paper architecture into a small network in 1969 intended to promote the sharing of supercomputers among researchers in the United States. The development of ARPANET into a global network of computers resulted in the Internet and WWW, containing the Hypertext Markup Language (HTML) which was released in 1991 by CERN.

The use of computers within design has also increased during recent decades, and computers are today a necessity for most engineers in their everyday work. With the tremendous expansion of the Internet/intranet there has been a vast variety of implementations of World Wide Web (WWW) applications that assist designers, see e.g. Huang and Mak (1999) and Liang et al. (1999). The conceptual layout of the current implementation will briefly be discussed next.

The implementation presented in this work is a Client/Server WWW application that combines FE analysis with DOE, in which computing resources within a network are efficiently utilized. An evaluation with the current implementation can be subdivided into several steps. In the first step a designer opens up a standard WWW browser, connects to the WWW server and retrieves the client-side user interface.

The problem to be evaluated is specified by choosing the ASCII text file containing the analysis data for upload to the server. The appropriate names and values of the design variables are assigned along with the definition of the responses that should be calculated in the analyses. The analysis data are submitted to the WWW server. The server starts the CGI (Common Gateway Interface) application that handles the FE analyses. If the analyses are to be performed on a single machine, e.g. on the WWW server itself, they are sequentially started based on the DOE layout. The statistical evaluation is carried out by the CGI application after they are completed. When the statistical evaluation is performed, the result is submitted back to the client side where the designer can view the result.

If, on the other hand, the analyses are chosen to be distributed on a cluster of computers, the FE analyses information is passed on from the CGI application to the master program of the WPVM (Windows Parallel Virtual Machine). The WPVM software is built upon the standard features of PVM compiled for the MS Windows operating system. WPVM is compatible with the original PVM, which means that virtual machines can simultaneously be composed of UNIX and MS Windows machines. The master program allocates the necessary or available computer resources and sends data to each slave program that executes the FE analyses. When all FE analyses have been executed, the resulting data are collected by the master and sent back to the CGI application for the statistical evaluation. After the CGI program is finished, the server sends the postprocessing HTML page back to the user who requested the evaluation. The central part of the postprocessing is a Java applet that serves as a file manager for all the users' studied projects. Every project contains a listing of the chosen analysis data and a presentation of analysis statistics.

In both cases of evaluation, the results are now obtainable for other designers and design teams from all over the Internet or intranet by connecting to the WWW server and retrieving data belonging to a specific evaluation. The postprocessing applet contains a subfolder named result containing another subfolder for each of the chosen response functions. The FE analyses results are visualized through Virtual Reality Modeling Language (VRML). The user has the possibility to rotate, zoom, translate and seek certain model locations of the VRML model with the built-in mechanism in the browser's plugin for handling VRML files. The folder further contains graphical presentations of the statistical evaluations through normal probability plots. The data representation in the normal probability plot is abstract but nevertheless an essential part of the evaluation, as it is the basis for further statistical evaluation of the results.
AN EXAMPLE

The example is presented to emphasize the possibilities that the PDA approach will give the designer in the work of finding a solid basis for evaluating different concepts. The product that should be developed is a lever. Four different conceptual designs of the lever, shown in Table 1, are considered. The lever should be able to transform displacements in point 1 to a displacement in the y-direction of point three by revolving around point 1. In the conceptual phase the most appropriate design concept with respect to the overall function should be sorted out. To make the FE analyses meaningful, they have to be made with the same basic physical assumptions, which in this case was established by using the same mass and thickness for all lever concepts. In addition, the mathematical representation of the levers should be made as simple as possible since the knowledge of each concept is far from complete in the conceptual design phase. The designs are therefore analyzed with one of the simplest FE representations available, which in this analysis are beam elements with 6 degrees of freedom at each node to allow both displacements and rotations.

Table 1: Layout of the four studied design concepts.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Design concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td><img src="image.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

Making use of the result provided by Bisgaard (1997), the four design concepts along with two two-level design variables are evaluated in sixteen FE analyses. The four design concepts are chosen as combinations of design variables A and B as shown in Fig. 3. The applied displacement at point 1 is chosen as design variable C, which due to external factors is able to move one unit either in the positive x-direction or in the negative y-direction. The last design variable (denoted D) is a torque, acting around the negative z-axis at point 2, which is modeled as either active or not to simulate a friction or frictionless joint.

Table: Statistical design layout for 4 variables in 16 analyses.

<table>
<thead>
<tr>
<th>Run</th>
<th>A</th>
<th>B</th>
<th>Concept</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>+</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>+</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>+</td>
<td>-</td>
<td>3</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>+</td>
<td>2</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>+</td>
<td>+</td>
<td>4</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>+</td>
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<tr>
<td>10</td>
<td>+</td>
<td>-</td>
<td>3</td>
<td>-</td>
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<td>+</td>
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<td>-</td>
<td>3</td>
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</tr>
<tr>
<td>16</td>
<td>+</td>
<td>+</td>
<td>4</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

The following additional boundary conditions were also used in the FE analyses:

- Point 2 was constrained in all degrees of freedom except for the rotation about the z-axis.
- Point 3 was constrained in all degrees of freedom.

Now everything is prepared and ready for performing the evaluation. The studied response is the reaction forces at point 1, which represent the stiffness that each design concept provides. The concepts that result in high reaction forces are interpreted as suitable conceptual solutions for the overall function.

After the FE analyses and the statistical evaluation are performed, the normal probability plot, as shown in Fig. 4, is accessible through the client-user interface. The plot should be interpreted as follows: Each point represents an effect of a design variable or an effect of combinations of two or more design variables, and those points that lie outside of the straight line have influence on the studied response. The applied moment at point 2, denoted D in Fig. 4, clearly has little influence on the response. It can be concluded that the friction as modeled in this example has no influence on the response and will not be studied further in the subsequent design phases. Figure 4 also shows that the displacement variable, denoted C in Fig. 4, and the choice of design concepts, denoted AB in Fig. 4, are active and thus influence the results.

Figure 3: Statistical design layout for 4 variables in 16 analyses.
The result in Fig. 4 above is presented in an abstract way; a more concrete way of viewing the results is presented in Fig. 5, in which the actual reaction force is plotted against each conceptual layout.

Figure 5 indicates that concept number four has high average reaction forces and that its sensitivity to direction of the displacements is acceptable in comparison with the other design concepts. The quantitative evaluation performed emphasizes concept number four as the most suitable. These results should now be evaluated along with other criteria that were specified for the lever during the planning and clarification task stages of the design process.

In this example the result from that evaluation is omitted since the use of PDA is independent of the previous evaluation although it contributes greatly to the knowledge of the behavior of the concepts studied. Based on the evaluation documented in this work, concept number four was chosen for further evaluation in the subsequent design phases. After the choice of concept has been made, the embodiment design phase is entered and the preliminary layout of the lever is to be studied. The FE model is refined and a 2D-plane stress model is considered. At this stage the embodiment of the lever is evaluated with five design variables of different physical nature. All design variables along with the assigned values are shown in Table 2. The influence of the section height and the section thickness is studied along with the displacements in point 1 as in the conceptual design phase. Further, the Young’s modulus and the spring constant of the applied spring at point 3 are considered.

Table 2: Design variables studied in the embodiment design phase

<table>
<thead>
<tr>
<th>Design variable</th>
<th>Description</th>
<th>Low value</th>
<th>High value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Section height</td>
<td>6e-3</td>
<td>13.5e-3</td>
</tr>
<tr>
<td>B</td>
<td>Section thickness</td>
<td>2.7e-3</td>
<td>6e-3</td>
</tr>
<tr>
<td>C</td>
<td>Displacement in point 1</td>
<td>x dir.</td>
<td>-y dir.</td>
</tr>
<tr>
<td>D</td>
<td>Young's modulus</td>
<td>1.4e11</td>
<td>3.2e11</td>
</tr>
<tr>
<td>E</td>
<td>Spring constant</td>
<td>20.7e3</td>
<td>46.5e3</td>
</tr>
</tbody>
</table>

The following boundary conditions were also used:
- Point 2 is constrained in all degrees of freedom except for the rotation about the z-axis.
- The spring is acting in the y-direction between point 3 and a point that is constrained in all degrees of freedom.

The responses studied are the displacement of point 3 and also the equivalent von Mises stress in the lever. The VRML graphics file in Fig. 6 shows the resulting Von Mises stress of one of the analysis configurations. A corresponding plot is available for all analyses performed, and the HTML page containing the graphics file can be retrieved with the client user interface.
Figure 7 shows the normal probability plot of the two studied responses. The most significant variable is the displacement variable i.e. in which direction the displacement at point 1 is applied. This variable has big influence on both the studied responses. The section height, section thickness and interactions between the displacement direction and the section data are also significant. In the normal probability plot of the displacement response there is also shown an influence of the spring constant.

The relationship between the displacement of point 3 and the active design variables is displayed in Fig. 8. The response is presented in two groups depending on the direction of the applied displacement at point 1. The values within each ellipse represent a constant mass of the lever. Based on the importance of the overall criteria, the designer can use Fig. 7 and Fig. 8 to determine the final design. When, for instance, low mass is desired the lower values of height and thickness should be used. If the displacement at point 3 is not allowed to be less than e.g. 0.5, the displacement at point 1 should be in the x-direction. If on the other hand the influence from the spring constant should be minimized, the displacement at point 1 should be in the y-direction. Other variable configurations can be found in the same manner as described above.

Figure 7: Normal probability plots of the studied responses in the embodiment design phase

Figure 8: The Java post-processing applet and cube plots of the displacement and the mass, both in unit of measurement, of point 3.
CONCLUSION

This paper presents the value of using DOE together with PDA within the design process to evaluate conceptual solutions in the early design phases, i.e. conceptual and embodiment design phases. When more complex products are considered, the basic approach of PDA is the same. The implication would be that more variables and other DOE algorithms have to be applied. The Client/Server implementation utilized facilitates the possibilities for designers in different design teams connected to the Internet/intranet to view and evaluate the statistical result simultaneously. The Client/Server implementation can be considered as an embryo of an interface that could serve as an umbrella for the overall development process independently of which analytical or statistical techniques are used to perform the actual analyses and evaluations. The fact that all analyses based on DOE are performed independently of each other makes them well suited for implementations of distributed processing on e.g. a cluster of computers connected through a network. The total evaluation time decreases rapidly when the number of computers utilized increases. In a company connected through an intranet the computing resources can effectively be allocated whenever the computers are not allocated for other duties.

By combining different evaluated responses into a decision table, and assigning them relative weights based on their importance to the overall criteria, the optimum design variable configuration can be established. The total development and manufacturing cost of a product can also be evaluated by studying the quality level of different manufacturing processes. Combining studies of the significance of estimated factor effects with the PDA approach gives the engineering designer a tool that has a potential similar to that of the robust design concept for comparing the distribution of the strength and the prescribed load distribution. To increase the use of both design analysis and statistical methods at the early phases of the design process, the proposed PDA approach will provide the designer with tools for using design analysis more effectively.

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Establishment of a foundation for predictive design analysis within the engineering design process

Eriksson, M.


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Abstract - In today’s highly competitive market place it is of great importance for companies to deliver reliable products while decreasing the development time and costs. The time to market is a driving force for many companies, and throughout the engineering design process as well as the manufacturing process, the focus is on finding timesaving actions. However, the search for timesaving actions will most certainly result in a loss in product reliability if it is not combined with improved techniques and tools used by members of the engineering design team in order to maintain an acceptable level of reliability.

One of the areas within engineering design that is adopting new techniques and methodologies is the design analysis activity that has conventionally been performed by specialists, but has to some extent shifted to also be performed, where applicable, by design engineers. Further, design analysis has traditionally been utilized as a verification tool at the latter engineering design phases and also for failure mode analysis with the objective to investigate failed designs or produce results about whether or not it will withstand applied loading conditions. Today both the research community and industry perceive the value added when design analysis is used in early engineering design phases to predict the performance of the product to be. Statistically planned and Stochastic (alternatively called in literature probabilistic) Finite Element Analysis (FEA) are addressed frequently in this area of research, and different mathematical methodologies have been discussed to provide this value-added information within design analysis. Fractional factorial designed experiments, Response Surface Methodologies (RSM) and Monte Carlo Simulations (MCS) are among the most commonly discussed approaches. One of the vital issues here is the shift from the deterministic design analysis approach, in which accounting for variations is done through safety factors that are overly conservative, to a Statistical or Stochastic design analysis approach where variables are defined in terms of their characteristics: the nature of the distribution of values, a typical value, and also, in stochastic approaches, a measure of the variability.

A presentation of Predictive Design Analysis (PDA) is made in this paper, which incorporates Statistical and Stochastic approaches to perform design analysis at different phases of the engineering design process. The PDA methodology addresses abounding uncertainties i.e. material properties, magnitude and direction of loading, part geometry as well as the issues regarding sensitivity to variables acting on the product in service, all of which result in performance that is considerably different from the ideal.

INTRODUCTION

In this paper the foundation for PDA is established. PDA was originally proposed by Bjärnemo and Burman [1] as a concept for handling the uncertainties accompanying the design of a product – from the establishment of the market need until the materialization of a complete physical prototype, incorporating all of the expected functions of the product. In the origination of the concept of PDA, methods and techniques for handling the uncertainties throughout the engineering design process was just briefly elaborated upon. However, the use of PDA in the conceptual design phase has been covered to some extent in Eriksson [2]. In the present engineering design methodologies the importance and relevance of different
functions within the engineering design process are frequently discussed within both academia and industry. There exist many general methodologies on the subject and also, in practice, most companies have a modified “in house” methodology that is adapted to their special needs. One common denominator, in these methodologies, however, is that of designing a product that satisfies a number of needs and demands on the product. Furthermore, most of the current methodologies discuss the design of products in the context of concurrent, integrated or simultaneous design, which means that the activities are more or less to be performed concurrently in order to increase the efficiency in the overall development process. Functions within the development process are among others manufacturing, marketing as well as industrial and engineering design.

Most methodologies begin by the product-planning phase where the selection, “portfolio”, of products to be developed is planned; see e.g. Ulrich and Eppinger [3]. The next activity in the engineering design process is the conceptual design phase, in which the generation of concepts that fulfill the criteria are identified through evaluation and decision-making, resulting in the most promising conceptual solutions.

In an intermediate phase, this concept is designed further, which is referred to e.g. by Pahl and Beitz [4] as embodiment design and by Ulrich and Eppinger [3] as system-level design. Note that these phases are just approximately identical. The objective for this phase is to design product candidates to a level of abstraction where detail designing is worthwhile. The detail design phase is where the engineering design is finalized in terms of e.g. geometry, material and tolerances. The phases of the engineering design process that will be discussed in this paper is:

- Conceptual design
- Embodiment design
- Detail design

Another topic that is important to address when designing products is the nature of the products to be designed. Pahl and Beitz [4] mention three types of product designs:

**Novelty**: New solution principles are introduced either by selecting and combining known principles and technologies, or by inventing new technology. 

**Adaptive design**: One keeps to known solution principles and adapts the embodiment to changed requirements. 

**Variant design**: the sizes and arrangements of parts and assemblies are varied within certain previously defined product structures.

Ulrich and Eppinger [3] presents a similar categorization:

- **New Platforms**: Creation of new family of products based on a new, common platform. 
- **Derivatives**: The products are an extension of an existing product platform. 
- **Improvements**: Products that are based on modified features on existing products. 
- **Fundamentally New**: Products that are based on different product and production technologies.

It is obvious that the procedures within the design process are quite different depending on what type of product is to be designed. Thus the number of design process activities utilized differs among different industries and also from project to project within a company.

**OBJECTIVE**

In the present paper the different statistical and stochastic mathematical procedures utilized within PDA is elaborated on. A generalized methodology for the utilization of these combined techniques is discussed and exemplified. The mechanical engineering design process, or design process for short, and Finite Element Analysis (FEA) are selected to exemplify the engineering design process and the design analysis techniques respectively. The general objective is to present the design analysts and/or design engineer with some general guidelines on how and when to employ different statistical or stochastic techniques, within PDA, to extract the appropriate amount of information at different levels of concretization of a product to be. The word design will occur in terms of both engineering design, design analysis and also in the term of statistical design of experiments, where it refers to the order in which experiments are performed.

**DESIGN ANALYSIS WITHIN THE DESIGN PROCESS**

Design analysis could be seen as analyses and simulations performed on computers that result in some quantitative or qualitative information (data/indication) of the product to be, which could be performed throughout the entire design process. A vast variety of techniques and softwares based on mathematical formulations exist and the mathematical method chosen to exemplify design analysis, in this paper, is the Finite Element (FE) Method (FEM); see e.g. Zienkiewicz [5]. FEM is selected because it is the most commonly used method in both industry and in the research community to perform analyses in “problem areas “ such as
analyses of multibody systems (MBS), structural analyses, thermal analyses, electrical analyses, magnetic analyses and computational fluid dynamics (CFD).

FEM is commonly used as a tool by engineering analysts and engineering designers to verify whether a product’s design can withstand the loading and environment to which it is subjected. Further, the method can be applied in both single deterministic static analyses, where the general overall behaviour is studied along with stresses and displacement, as well as in complicated optimization problems, where the goal is to find the most suitable design for the given premises. Approaches where FEM is treated as an engineering design tool and not exclusively as verification tool that could be integrated with most methodologies to the design process have been addressed more frequently in recent years.

When performing design analysis, a number of uncertainties concerning physics and numerical simulation techniques have to be considered. In general terms the analyses are often referred to some level of complexity that relates to dependency of a response on different variables and uncertainties. Marczyk [6], among others, has summarized these uncertainties into a few categories, which are listed below, with some different examples in comparison with the original text.

1. Loads (static, dynamic, impacts, etc.)
2. Boundary and initial conditions (stiffness of support, velocities, etc.)
3. Material properties (stress-strain data, density, imperfections, etc.)
4. Geometry (shape, assembly tolerances, etc.)
5. Modeling uncertainty (level of abstraction, lack of knowledge, etc.)
6. Mathematical uncertainty (accuracy of the model)
7. Discretization error (discretization of BCs, etc.)
8. Programming errors in the code used
9. Numerical solution errors (round off, etc.)

The first four categories concern physics, and the other five categories deal with the numerical simulation, which is designed to mimic the physics. In most, if not all, design analysis performed the numerical simulation uncertainties are active, but of course probability for influence on the result will increase when more advanced FEM formulations are used.

Thus, the level of accuracy of the response is highly dependent on the input data and the design analysis techniques used. Therefore the establishment of an adequate objective, relevant variable setting and correct response is as important as the execution of the analysis.

STATISTICALLY PLANNED AND STOCHASTIC DESIGN ANALYSIS

In terms of statistics the traditional ways of performing design analysis could be referred to as the one-factor-at-a-time approach or the “best guess” approach. The latter approach often works reasonably well due to the fact that the analysts often have a great deal of technical or theoretical knowledge of the system. However, there are obvious disadvantages to this approach. Consider the case where the initial best guess does not produce the desired results; then another “best guess” must be made, and this could, in the worst case, be repeated many times without any guarantee of satisfactory results. Secondly, what if the first best guess is acceptable? Should another analysis be performed, or should the initial variable configuration be accepted without knowing anything about the variability of the solution?

In the one-factor-at-a-time approach, in which the analyses are performed by first selecting a starting point for each factor, then successively varying each factor over its range with the other factors held constant. This can be illustrated with Figure 1 where three variables A, B and C are studied. As can be seen, one factor at a time gives results at four corners of the design space. It is quite obvious that any interaction effects among the studied variables are neglected.

Figure 1. The one-factor-at-a-time approach.

A more scientific approach to the problem is to reason out all the factors that might affect the response and then perform a number of systematically planned analyses for these variables. In the context of statistics a variety of methods exist, and in the area of design analysis two approaches are commonly used. These methods are statistically planned experiments also referred to as Design of Experiments (DOE) and stochastic simulations, which will be outlined in the next two sections.
DESIGN OF EXPERIMENTS

The primary objective of industrial DOE is to extract as much information as possible with a reasonable number of experiments. One of the basic ideas behind DOE methodologies is the assumption that lower order effects are more likely to be important, which is often called the Pareto effect. It is often concluded that for engineering problems the main effects and the two factor effects, which are the interaction between any two main effects, are the important effects; see e.g. Bisgaard [7].

The often-used experimental design layouts within industrial experimentation are: $2^k$ designs (two-level), $3^k$ designs (three-level), mixed designs (with 2, 3 and more level factors), Latin square designs, Taguchi methods, central composite designs (used mainly in the response surface method) and screening designs for large numbers of factors such as Placket Burman designs. Detail description of these designs can be found in standard textbooks such as Box et al. [8], Montgomery [9]. However, some short notes for the different design layouts will be presented for the completeness of the current paper.

Factorial designs: The most intuitive approach to study the variables would be to vary the factors in a full factorial design, that is, to try all possible combinations of settings. Figure 2 displays the design points, with a cube plot, for four variables A, B, C and D in 16 runs.

![Figure 2. Factorial design with four variables.](image)

The factorial approach can always be applied, but the downside is that the number of necessary runs (observations) in the experiment will increase dramatically with the number of variables. Whenever fewer experimental runs are requested in an experiment than would be required by the full factorial design, a "sacrifice" in interaction effects is required. The resulting design is no longer a full factorial but a fractional factorial.

Furthermore, based on the Pareto effect, three-factor and higher order interactions are usually not significant in engineering design applications. Therefore a fractional approach that allows the lower order effects to be estimated would be more economical. One such fractional design would be to take a half fraction of the design, e.g. half the number of experiments (8 runs), which is referred to as $2^{4-1}$, where 4 denotes the number of variables and $\frac{1}{2}$ denotes the fraction. Table 1 shows the design layout for a $2^{4-1}$, where each row is called a contrast that specifies the combination of settings for each run, and $-1$ denotes the lower variable level and $+1$ the higher.

<table>
<thead>
<tr>
<th>Run</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Variables</th>
<th>Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>Y1</td>
<td>+1 -1</td>
</tr>
<tr>
<td>2</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>Y2</td>
<td>-1 +1</td>
</tr>
<tr>
<td>3</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>Y3</td>
<td>-1 +1</td>
</tr>
<tr>
<td>4</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td>Y4</td>
<td>+1 -1</td>
</tr>
<tr>
<td>5</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>Y5</td>
<td>+1 +1</td>
</tr>
<tr>
<td>6</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>Y6</td>
<td>-1 -1</td>
</tr>
<tr>
<td>7</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td>Y7</td>
<td>-1 -1</td>
</tr>
<tr>
<td>8</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>Y8</td>
<td>+1 +1</td>
</tr>
</tbody>
</table>

The key issue is how this fraction should be chosen in order to get an orthogonal matrix. In the standard $2^{4-1}$ design the fourth variable D is taken as the product of the columns for factors A, B and C, which means that each entry in the column D is equal to the product of the corresponding entries in the columns for A, B and C. Since the column for D is used for estimating the main effect of D and also for the interaction effect between A, B and C, the data from such a design is not capable of distinguishing the estimate of D from the estimate of AxBxC. The factor main effect D is said to be aliased, or confounded, with the AxBxC interaction. A usual notation of this aliasing relation is D=ABC or I=ABCD, where D=ABC is often referred to as the design generator. Further, I denotes that the product of the four columns A, B, C and D is all positive and is referred to as the defining relation. The $2^{4-1}$ design is said to have resolution IV because the defining relation consists of the word “ABCD”, which has the length of four letters. In general, a design of resolution $R$ is one where no $l$-way interactions are confounded with any other interaction of order less than $R-l$. In the current design, $R$ is equal to 4. Thus, no $l = 1$ level interactions (main effects) are confounded with any other interaction of order less than $R-l = 4-1 = 3$. 

![Diagrams](image)
In the Resolution IV design above, each of the four main effects A, B, C and D is estimable if the respective three factor interaction alias is negligible, which is as stated before the usual case in engineering design situations. One desirable characteristic of any design is that the main effect and interaction estimates of interest are independent of each other. Further, when the factor level settings for two variables in an experiment are uncorrelated, that is, when they are linearly independent of each other, then their columns are said to be orthogonal.

Thus for an orthogonal design the Dot product between any two columns is zero, see e.g. columns 1 and 2 in Table 1:

\((-1)^* (-1)^+ 1^* (-1)^+ (-1)^* 1^+1^+(-1)^* (-1)^+ 1^*(-1)^+ (-1)^* 1^++1^+1^+1^+1^=0\)

Randomization of the order in which the experiments are conducted reduces the unwanted effects of other variables not included in the experiments. However, when performing computer experiments together with FEM, randomization has no point since all replicates of an experiment will result in the same response independently of the order in which they are performed.

A replicated experiment means that the experimental plan is carried out two or more times. This allows for estimation of the so-called pure error in the experiment and also the computation of the variability of measurements within each unique combination of factor levels. Replication is unnecessary for computer experiments because repeated computer runs with the same input result in the same output.

Plackett-Burman Designs for Screening

When one needs to screen a large number of variables to identify those that may be significant, the employment of a design layout that allows testing the largest number of variable main effects with the least number of experiments is of interest. In terms of resolution, a resolution III design must be used with as few runs as possible. Plackett and Burman showed how full factorial design can be fractionalized in a different manner, to yield saturated designs where the number of runs is a multiple of 4, rather than a power of 2 as for fractional $2^{k-p}$ designs. These designs are also sometimes called Hadamard matrix designs.

Experiments with variables at three levels.

The main differences between two-level designs and three-level designs are the fact that each three-level variable has two degrees of freedom and there are two systems for parameterize the interaction effects in three-level designs: the orthogonal components system and the linear-quadratic system. The situations in which changing to a three-level design is needed are:

- A quantitative variable may affect the response in a non-monotone fashion. Three or more settings are required to detect a curvature effect. The Composite design techniques, discussed later, combines a two-level factorial or fractional factorial design with additional levels to account for non-linear response.
- A qualitative factor may have several levels, such as three cross-section layouts.

Latin Square Designs

Latin square designs are used when the variables of interest have more than two levels and when there are no (or only negligible) interactions between factors. For example, in an experiment with four variables at four levels a full factorial design could be utilized, resulting in 256 experimental runs. However, if the objective of the experiment were to estimate main effects, the Latin square design with 16 runs would estimate 4 unconfounded main effects.

Taguchi methods

To briefly describe the Taguchi methods in the context of statistically designed experiments, it can be concluded that the design layouts presented by Taguchi can often also be found among Western statisticians. The approach differs in the way that the variables are explicitly categorized as control and noise factors, and the design plans are divided up with inner and outer arrays for easier evaluation of interaction effects of noise and controllable factors. In the evaluation of the experiment, the factors that most strongly affect the chosen S/N ratio are established, where the S/N ratio is divided up into three groups, Smaller-the-better, Nominal-the-best and Larger-the-better, based on the current objective of the experiment.
Statistical evaluation of data

The main effect of a variable in an experiment is calculated as the average change in the response for e.g. variable A in Table 1:

\[ A = \frac{(Y2 + Y4 + Y6 + Y8)}{4} - \frac{(Y1 + Y3 + Y5 + Y7)}{4} \]

When the effect of variable A is affected by changes in another variable, say variable B, the variables A and B are said to interact. The effect of interaction AB in Table 1 is calculated as:

\[ AB = \frac{(Y1 + Y4 + Y5 + Y8)}{4} - \frac{(Y2 + Y3 + Y6 + Y7)}{4} \]

The interaction effect of variables CD is established in the same way and is equal to the interaction effect of AB. The resolution four designs cannot distinguish any two-factor effect from another two-factor effect. The responses as well as the established effects in the statistical evaluation can be graphically displayed in a couple of ways, which will be discussed next.

**Pareto chart plots.**

The Pareto chart plot of effects is often an effective tool for communicating the results of an experiment. The magnitude of each effect is represented by a column (independent of sign), and often, a line going across the columns indicates how large an effect has to be to be statistically significant.

**Normal probability plot of effects.**

Plot the ordered values of the factorial effect estimates against their corresponding coordinates on the normal probability scale by fitting a straight line to the middle group of points where the effects are near zero. Any effect whose corresponding point falls off the line is declared significant. The rationale behind this graphical method is as follows. Assume that the estimated effects are normally distributed with equal means. The normal probability plot is testing whether all of the estimated effects have the same distribution, so that when some of the effects are non-zero, the corresponding estimated effects will tend to be larger and fall off the straight line. For positive effects, the estimated effects fall to the right of the line while those for negative effects fall to the left of the line. A positive effect is an effect where a shift from a low level to a higher level results in a decrease in the response; a negative effect will correspondingly result in an increase in the response for the same shift from a low level to a higher. When estimating the significance of variables in a normal probability plot, not only the departure from the straight line but also the magnitude of effects must be considered. The significant variables are those with highest positive or negative values.

**Plot of mean and interaction effects**

There exist many different ways of displaying the evaluation of main and interaction effects. Three methods for displaying the responses are the **plot of means** and the plot of interaction together with the cube or rectangle plot. In the **interaction plot** the mean values for two variable interactions are plotted as points that are connected by lines. Another type of plot is the rectangle or cube plot. These plots are often used to summarize the response values for two, three or four variables, given the respective high and low setting of the variables.

**Diagnostic plots of residuals.**

As a basic evaluation of the results from an experiment, one can examine the distribution of the residual values. This is the good starting point for model verification. The residuals are computed as the difference between the predicted values (as predicted by the current model) and the observed values. The residuals can be plotted in two different ways; either by plotting them against the variables or by the normal probability plots, where the residuals should plot roughly as a straight line. A marked deviation of the plot from a straight line indicates that the mathematical model of the response is not adequate.

**Response Surface method**

The Response Surface Method (RSM) is designed for experiments where the objective is to describe how the response varies as a function of more than one variable; see e.g. Montgomery [9]. The response surface approach constructs smooth functions (e.g. first-order or second-order), often polynomials, which are used to establish an approximation of the response (also called the objective function) through a number of selected experiments, usually executed as "extended" DOE. Thus, with RSM the variable settings that correspond to a desired value in the response can be extracted. The most popular extended DOE utilized in response surface design is the Central Composite Design that is constructed by combining a two-level fractional factorial...
(corners of the cube), and two other kinds of points defined as follows.

Center point for which all the factor values are at the zero (or mid-range) value. Axial points, for which all but one factor are set at zero (mid-range) and one factor is set at outer (axial) values as displayed in Figure 3.

![Figure 3. Central Composite Design.](image)

The response surface function is established through a regression model that is a least-squares fit of the variables studied. A first-order model describes flat surfaces that can be tilted and are thus separated from curved regions like the maxima, minima, or ridgelines. To be able to estimate a curved region, a second-order model has to be adopted. One thing that has to be kept in mind when working with response surface is that these describe local areas. Thus, the description will usually not fit the entire design space of the variables. So, if different regions have to be described, additional experiments for those particular variable settings are needed. However, the model can be utilized to instruct in which direction the variables should be moved, through the mathematics of e.g. steepest ascent method.

Certainly the approximate optimum found on the response surface has to be checked at least for admissibility with an explicit experiment of the design. If there is significant difference within the evaluation of the objective function, an adaptive refinement process of the response surface with calculation of additional support points may become necessary. Recommended areas of application are reasonably smooth problems with a maximum of 30-50 variables depending on the complexity of the problem.

**Summary of Design of Experiments**

The factorial and/or fractional experiments give the effect of each variable and they also reveal interactions between variables. Interactions between noise variables and design variables can be exploited. However, the simplicity of these designs is also their major flaw. As mentioned above, underlying the use of two-level factors is the belief that the resultant changes in the dependent variable are basically linear in nature. Thus, one cannot fit explicit non-linear (e.g., quadratic) models with $2^{k-p}$ designs. However, this is sometimes not the case, and many variables are related to quality characteristics in a non-linear fashion and also in some case in a non-polynomial fashion. The non-linear type of curvature in the relationship between the responses in the design and the significant variables cannot be detected unless experiments are made at the variables center points. Depending on the complexity in the response at the current variable levels in a non-polynomial situation a polynomial might be an adequate approximation of the response at these levels.

Another problem of fractional designs is the implicit assumption that higher-order interactions do not matter; but sometimes they do. For example, when some other factors are set to a particular level, a variable may be negatively related to another variable.

To be able to determine whether or not the used model is adequate the diagnostic plots of residuals should be established, which is a powerful tool to validate the selected model. In situations where problems are found through the plots of residuals the response should be further investigated by additional analyses or some adequate transformation of the responses.

**STOCHASTIC SIMULATIONS**

When the number of variables being investigated increases, the resource requirements with the statistically designed experiments could be too large. Further, optimal designs often have the tendency to be very sensitive to small (sometimes random) fluctuations of variables. Such phenomena may occur due to system instabilities like bifurcation problems in the structure; see e.g. Marchyk et al. [10]. Since the evaluation of sensitivity to variable changes of the most favorable final design is important, the adoption of a systematic stochastic analysis provides an efficient way in which this can be checked. The problem that has to be recognized, however, in dealing with stochastic equations, is two-fold. Firstly, the random properties of the system must be modeled adequately as random variables or processes, with a realistic probability distribution. Secondly, the resulting differential equation of response quantities must be solved. From a design process perspective, most common systems can be seen as stochastic systems involving differential equations, typically linear, with random coefficients. These coefficients represent the properties of the system under investigation. They can be thought of as random variables or, more
accurately and with an increasing level of complexity, as random processes with a specified probability structure. Two different approaches to stochastic modeling will be presented in this work: Perturbation Methods and Monte Carlo Simulations.

**Perturbation Methods**

Sensitivity methods have been utilized within design analysis for quite some time in the area of optimization. One of the basic components of an optimization scheme is the establishment of derivatives, which is usually done by some kind of sensitivity analysis; see Bazarra et al. [11]. This basic mathematical formulation has been applied to FEM and has been given the name Stochastic Finite Element Method (SFEM), that is a sensitivity-based FEM. Haldar and Mahadevan [12] present a more in-depth explanation of the approach. They state that the search for the design point in many practical problems converges within 10 or 20 iterations and that the gradient of the value function at each of these iterations is required. The value function is established through a deterministic analysis, and the gradient is computed with a sensitivity analysis. Two of the available approaches to sensitivity analysis are the finite difference and the perturbation approaches. The finite difference approach (forward or backward) utilizes a number of deterministic analyses in order to establish the derivatives. The number of analyses needed is \((n+1)^m\) times, where \(n\) is the number of random variables and \(m\) is the number of iterations to find the solution. Thus when the number of design variables increases the total analysis times will also increase. For a problem with 4 design variables, the number of analyses will be around or above 50. Keep also in mind that this is needed for each response studied such as displacement, stress and weight. Thus the overall analysis time could be unacceptable.

In the approach of perturbation the fact that basic design variables are often stochastic in nature means that the computed responses are also stochastic. To be able to estimate the variation of the response at every deterministic analysis it is strategic to express it in terms of the variation of each design variable at every deterministic analysis. This is done by simply applying the chain rule of differentiation to compute the derivatives of the structural response with respect to the design variable, which is often referred to as classical perturbation. The mathematical simplicity of the perturbation method makes it useful in a wide range of problems. The perturbation scheme consists of expanding all the random quantities around their respective mean values via a Taylor series. The larger the magnitude of the random fluctuations, the more terms should be included. As mentioned earlier, computations beyond the first or second order terms are usually not practical in engineering design problems. If such higher order terms were to be included, the mathematical computation could become very complicated. On the other hand these lower order terms restrict the applicability of the method to problems involving small randomness.

It can be concluded that the method cannot be readily extended to compute the probability distribution function of a general response over the whole variable design space. Another drawback with the perturbation approach is that the source code of the problem at hand has to be modified. The partial derivatives of the response with respect to each design variable must be computed at each iteration of the overall analysis technique.

**Monte Carlo Simulation**

Monte Carlo Simulation (MCS) is a quite versatile mathematical tool capable of handling situations where most other methods fail. This computational accessibility has triggered an urge to develop advanced and efficient simulation algorithms. The usefulness of MCS could be described as: the next best situation to having the probability density function (pdf) of a certain random quantity is to have a correspondingly large population approximating it. The implementation of MCS consists of numerically simulating a population corresponding to the random quantities in the physical problem, solving the deterministic problem associated with each member of that population, and thus obtaining a population corresponding to the random response quantities. This population can then be used to obtain statistics of the response variables. The only requirement, in MCS, is that the physical (or mathematical) system can be described by its pdfs. Once the pdfs are known, the MCS can proceed by random sampling of points from the pdfs. The outcome of these random samplings, or trials, must be accumulated or tallied in an appropriate manner to produce a solution of the physical problem. Thus a solution can be formulated in terms of pdfs, and although this transformation may seem artificial, it allows the physical problem to be treated as a stochastic process for the purpose of simulation, and hence MCS can be applied to simulate the physical problem. The primary components of a Monte Carlo simulation method include the following:
**Probability distribution functions (pdfs)**
The physical system must be described by a set of pdfs. These pdfs can originate from the basic distributions, for example Normal, Exponential, and Uniform.

**Random number generator**
Random numbers distributed on the unit interval must be established. These numbers are established by some applied sampling rule.

**Scoring (or tallying)**
The individual trials should be accumulated into overall scores for the responses of interest.

**Error (or variance) estimation**
An estimate of the statistical error within the experiment should be determined.

**Error (or variance) reduction techniques**
Methods for reducing the error in the estimated response should be utilized.

One drawback of MCS is that if the analyses are time-consuming, the high number of analyses executed could be impractical if only basic statistics are to be extracted. Furthermore, if the information regarding the physical problem is limited the pdfs could be hard to establish correctly.

**Statistical evaluation of data established in a stochastic approach**

The evaluations of stochastically generated results are performed by statistical evaluations. The evaluation is generally based on the assumption of the central limit theorem and the interdependency among the studied responses. Graphical presentations of the results are often in the form of Histograms, where the responses are divided up into certain intervals, cumulative distribution functions and scatter plots (also called ant-hill plots) in which the responses are plotted versus each one of the variables studied. Further outcomes from the statistical evaluations are e.g. mean value, standard deviation, and correlation coefficients between studied variables. These basic quantities can be used for regression and in the establishment of response surfaces.

**PDA IN THE ENGINEERING DESIGN PROCESS**

In all of the different disciplines discussed above (design process, experimentation and design analysis) the fundamental criteria for success are a well-founded objective and thorough establishment of possible important variables. All the established variables and objectives should be organized by their nature: industrial design, engineering design and manufacturing etc. The variables that should be used in the PDA activity should be extracted and sorted into controllable variables, and uncontrollable variables (noise). Also, depending on prior product knowledge and information, and keeping in mind the different types of product designs mentioned above, the investigations could be conducted more or less in depth. When a variant, or derivative product is to be designed the design space of the significant product variables and the critical objectives are to some extent already known. If on the other hand a novelty or fundamentally new product is designed, more in-depth work, concerning establishment of variable to be utilized, has to be performed through e.g. benchmarking against similar products.

Commonly complex systems are also divided up into subsystems that are designed in parallel with interface functions and relations connecting them. Of course this subdivision introduces additional uncertainties throughout the design process, which are recognized but not addressed further in this work.

**UTILIZATION OF PDA IN CONCEPTUAL DESIGN**

The objective within the conceptual design phase is to generate a concept that is only designed to the concretization level of a principle solution. When designing variants of existing products, the conceptual solutions are already established and the conceptual design phase, in the terms mentioned above, has a subordinated importance and is sometimes omitted in such projects. When dealing with products with new solution principles, on the other hand, the conceptual design phase is of utmost importance, since decisions made early in the design process often become increasingly expensive to modify in later phases of the design process. The problem, however, in early design phases is the lack of in-depth information. One part of the conceptual design phase, and also throughout the later phases, is to establish and refine the information as the project progresses. Thus, the PDA conducted in the conceptual design phase should support the activity of establishing information that is used to resolve the most promising concept of those that are evaluated. PDA should be performed with the objective to explore and enhance the information that can be investigated with design analysis methods. Although, the information available about variables studied might be inadequate for stochastic modeling, it could be suitable for fractional factorial or other statistical design layouts. Therefore the proposed methodology for the utilization of PDA in the conceptual design phase is based on factorial
and fractional factorial experiments. Also, adequate modeling of geometry, material and load conditions, among other things, must be done to facilitate simplified and fast analyses while nevertheless resulting in relevant responses. Fractional design layouts can also be utilized to compare different concepts with each other where concepts are seen as a variable with a discrete number of levels. A design problem with three beams, displayed in Figure 4, will be used to exemplify the possibility of sorting out vital variables. The overall objective in the project is to keep the displacement of point 1, in Figure 4, lower than 5 mm. A screening $2^4-1$ fractional design is used to plan 16 FEA with the software ANSYS. The analyses are performed as linear static analyses with linear steel material properties. The geometry is modeled with beam elements with rectangular cross sections with thickness of $0.5e-3$ m. The units in Figure 4 are all in standard SI units (m and N). Beam 2 is fully constrained at the right and the constraint at beam 1 is varied over the analyses. Also the placement of horizontal force (Fx) is varied over the analyses.

The response evaluated is the total displacement of point 1 in Figure 4. The main effect plot for the displacement response is displayed in Figure 5, where the average response is indicated with the dashed line.

From Figure 5 it can be seen that the displacement response clearly varies for the variables D, E and F, i.e. the cross sections of beams 1 and 2 and the BC of beam 1. To investigate the result further, the pareto plot of effects for the displacement response is established is displayed in Figure 6.

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The objective of the evaluation is to sort out the significant variables from the eight selected regarding the displacement of point 1. The variable levels (variables A through H) are listed in Table 2.

Table 2. Variables utilized in the example.

<table>
<thead>
<tr>
<th>Name</th>
<th>Low level</th>
<th>High level</th>
</tr>
</thead>
<tbody>
<tr>
<td>A L 1</td>
<td>0.4 m</td>
<td>0.5 m</td>
</tr>
<tr>
<td>B L 2</td>
<td>0.3 m</td>
<td>0.4 m</td>
</tr>
<tr>
<td>C L 3</td>
<td>0.3 m</td>
<td>0.4 m</td>
</tr>
<tr>
<td>D Cross section beam 1 height x width</td>
<td>0.03 m</td>
<td>0.04 m</td>
</tr>
<tr>
<td>E Cross section beam 2 height x width</td>
<td>0.03 m</td>
<td>0.04 m</td>
</tr>
<tr>
<td>F BC of beam 1 (constraints)</td>
<td>All</td>
<td>ux, uy, uz</td>
</tr>
<tr>
<td>G Fx (10kN) beam 2 beam 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H Angle α</td>
<td>0</td>
<td>5°</td>
</tr>
</tbody>
</table>

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From Figure 5 it can be seen that the displacement response clearly varies for the variables D, E and F, i.e. the cross sections of beams 1 and 2 and the BC of beam 1. To investigate the result further, the pareto plot of effects for the displacement response is established is displayed in Figure 6.
The effects that expand above or below the two dashed lines are said to be significant. The main effects of variables D (l8), E (l7), F (l14) and possibly also the AdxBHxCGxEF (l9) interaction effect are found significant. The interaction effect confounds different two-factor effects, but since both variables E and F are significant this interaction effect are most likely to be dependent on these two variables. Further, variable F are said to have a positive effect, which means that a shift from the lower level to the higher level of variable F results in an increase in the response, see Figure 7. Variables D and E have a negative effect and thus will influence the result in the negative direction. A Cube plot consisting of the significant variables is displayed in Figure 7. In each corner of the cube is the average of the two analyses performed at this variable configuration presented (units in mm). The cube plot displayed in Figure 7 illustrate the fact that the response is more dependent on the change of variable F than on variables D and E. It can also be seen that the effect of variable E is greater when F is at its higher level, which is due to the established interaction effect displayed in Figure 6.

![Figure 7. Cube plot for variables D, E and F.](image)

The information, regarding the total displacement of point 1, extracted from these sixteen analyses is that cross sections of beams 1 and 2 have to be studied further. The influence of the boundary condition applied on beam 1 is also important.

Generally the information gained from Fractional factorial designed analyses has to be incorporated into the decision-making procedures in the overall concept evaluation along with other criteria on the product to be, not analyzed with PDA to facilitate concept selection.

**UTILIZATION OF PDA IN EMBODIMENT DESIGN**

In the embodiment design phase the concept that was selected in the conceptual design phase are designed further. The factorial or fractional factorial design layouts, utilized in the conceptual design phase, in which the variables are evaluated at two levels, the implicit assumption is that the effect of the factors on the dependent variable of interest is linear. Hence it is impossible to test whether or not there is a non-linear (e.g., quadratic) component in the interactions among the variables. A so-called center-point run could be conducted to estimate whether the nature of the response is curve-linear or not, which is relevant for the later best-solution search in the detail design phase. In the current example is the influence of the boundary conditions at beam 1 investigated and a decision to fully constrain both beams are made. The effects of the cross sections of beams 1 and 2 are studied further with fractional analyses and RSM. First are four factorial designed FE analyses with variables D and E at two levels in which the other variables are all, except variable C, taken at their lower levels. Variable C is taken at its higher level. The displacement response (displacement in mm) for point 1 from these four analyses is displayed in the circles in Figure 8. A fifth analysis performed at the center location for both variables D and E, displayed with the lower red triangle in Figure 8. The displacement response displayed Figure 8 is reasonably close to linear and a first order RSM is adopted for the investigation of design space of the variables.

From the initial factorial designed analyses are three additional analyses performed, displayed with green dots. The variable levels for these analyses are established by calculation of the steepest descent. The direction of the steepest descent is indicated with the dashed line in Figure 8. At variable configuration (D=55 mm and E=45 mm) the total displacement is below the objective of 5 mm. To investigate the behavior of the displacement response in the neighborhood of these variable levels are five additional analyses, similar to the first five analyses, performed.

![Figure 8. Result of the RSM analyses.](image)
From the RSM analysis the design space of the two variables was searched in a systematic manner and a variable configuration that fulfilled the requirement on the displacement of point 1 was established.

**UTILIZATION OF PDA IN DETAIL DESIGN**

The objective within the detail phase is to finalize the product, which should fulfill the established requirements for the product. Obviously most design analyses are performed within the detail design phase, since at this phase much information regarding the input variables is available in terms of value levels, tolerances or variations.

The products designed should in some sense be best solutions but at the same time not be sensitive to variations in the variables, especially the noise variables. An optimal variables setting can be established with traditional optimization techniques. However, in engineering design additional information regarding the sensitivity of the best solution is of greater importance. Obviously DOE techniques such as factorial, fractional designs and RSM techniques can produce some of this information, but when the level of requested accuracy in the result is high the utilization of stochastic techniques is preferable. Within the stochastic approaches the perturbation approach requires access to analysis software, or the source codes for such software, that is able to extract the adequate derivatives of the response functions. This is, however, often not available when a general complex analysis is to be evaluated. Since it is simple to execute MCS trials and to evaluate and display the results, the MCS is proposed within PDA for these complex and detailed analysis situations in the detail design phase. Further MCS can be applied to most engineering analyses. Consider again the example outlined in Figure 4. The beam is in exceptional situations supposed to crash into an obstacle. The sensitivity to variations in the variables displayed in Figure 9 is studied. An MCS was performed with 100 trials where all stochastic variables are considered normally distributed and the variable names are given along with their average value and standard deviation (average, standard deviation) in SI units. Stochastic variables included in the analyses, regarding the three quadratic beams, are; a total of twelve thicknesses (5E-4, 5E-5), three Young’s modulus (2.1E11, 1.5E10), three yield stresses (250E6, 15E6) and three densities (7850, 100). The cross height and width of beam 1 is (0.06, 0.002) and the height and width of beam 2 is (0.04, 0.002). For beam 3 is the width taken as (0.04, 0.003). The thirty-seventh and last variable that was modeled as a normal distributed variable was the friction coefficient (0.3, 0.01) in the model.

![Figure 9 General layout of the impact example.](image)

The geometry is modeled with first order shell elements and the material properties are modeled with a piecewise linear plasticity formulation. For each of the hundred trials requested responses can be extracted and displayed. The displacement in y-direction of point 1 is displayed in Figure 10 for all trials.

![Figure 10 Displacement in y-direction of point 1.](image)

The scatter plot of the displacement in y-direction of point 1 versus the angle $\alpha_3$ of the obstacle is displayed in Figure 11.

![Figure 11 Scatter plot of the displacement in y-direction of point 1 versus angle $\alpha_3$.](image)
As can be seen in Figure 11 the displacement in y-direction of point 1 show dependency on the angle \( \alpha_3 \). If the beam is hitting the obstacle with positive angles of \( \alpha_3 \) the displacement in y-direction of point 1 are generally negative. The response can also be expressed in the statistical values of the average response, 0.02 m, and the standard deviation, 0.06 m². These analyses (trials) conducted with MCS could be utilized for correlation of computer analysis (virtual prototype testing) and physical testing, in which the general trends in the response clouds are equally important as each single experiment. When the response clouds of both the analyses and the tests have the same basic shape, it can be concluded that the correlations between the physical test and the design analysis model that mimics the physics are good. Assume that the above situation is investigated, without the knowledge presented in Figure 11, with one single analysis and a single physical test at zero hitting angle. In the computer analysis this is easy to establish, but in the physical test it can be harder to establish. If the angle is off the zero location, which is more likely to be the case than that it is actually zero, the results will differ. However, if PDA is performed together with a number of tests any difference in results between the design analysis and the physical test can be investigated and explained with a high level of confidence, which is not possible without having a reasonable number of responses.

**CONCLUSION**

In this paper is the use of statistical and stochastic methods within PDA outlined. The benefits as well as the drawbacks of different methods and approaches are discussed, and the value of introducing the PDA activity within different phases of the design process has been outlined mainly in terms of statistics. The subject of combining PDA and other problem solving techniques within the engineering design process has been addressed only briefly. This is, however, an important and vital part of the ongoing research on PDA and will be presented in future publications.

Although the current work discusses the topic of PDA within mechanical design, the general ideas can be applied in other areas of engineering design, such as electrical or chemical engineering design, wherever design analysis can be performed. The conclusion of the current work is that with increasing computational capabilities and enhanced mathematical formulations the proposed methodology will increase the probability for the designer or analysts to make appropriate decisions throughout the entire engineering design process.

**REFERENCES**


Paper III

Investigation of the exogenous factors affecting the design analysis process

Eriksson, M. & Motte, D.

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INVESTIGATION OF THE EXOGENOUS FACTORS AFFECTING THE DESIGN ANALYSIS PROCESS

Martin ERIKSSON, Damien MOTTE
Lund University, Sweden

ABSTRACT
Computer-based design analysis activities are an essential part of most product development projects in industry. An effective integration of the analysis activity into the product development process is therefore very valuable. The current work shows that design analysis activities are constrained and influenced by many elements from their working environment. Factors exogenous to the design analysis activity, but that have an important effect on it, are identified and grouped along their levels of influence on the activity: some appear within the development project, some are at the enterprise level, and some are outside the sphere of the enterprise. The proposed classification has the advantage of indicating what leverage a stakeholder can have upon such factors: the farther from the analysis activity context, the more difficult it is to act upon them. Furthermore, a guideline presents how to deal with these factors during design analysis planning and execution within a product development project and in alternative enterprise configurations. Being aware of those factors should prevent fastidious iterations resulting from a poorly planned and organised design analysis task.

Keywords: simulation, integrated product development, design process, design analysis

Contact:
Martin Eriksson
Division of Machine Design / Lund University
Department of Design Sciences LTH
Lund
SE-221 00
Sweden
martin.eriksson@mkon.lth.se
1 INTRODUCTION
In the large majority of development projects, solution proposals are evaluated with the help of computer-based design analysis tools. The more advanced the project is, the more detailed and complex the analysis can be, and, often, the analysis activity is performed by a specialist, employed by either the development enterprise or an engineering consulting (EC) company. The place of these analyses in a development project is important as they contribute to the exploration of design properties; evaluation and verification of design solution proposals; to the improvements/modifications of the studied design; to support the validation of the developed design; to reduce the required use of physical testing, etc. At the same time, computer-based design analyses are time-consuming, and much iteration is necessary between the engineering designer and the analyst before a final design is approved. A correct and effective integration of the analysis activity into the development process and in its working environment in general is therefore very valuable. However, apart for some early works at a time when computer-based design analysis was in its infancy (e.g. Ciarelli, 1990; Bjärnemo et al., 1991; Goss, 1991), this integration aspect of the analysis task into product development has been prioritised neither in the engineering design literature (see e.g. Pahl et al., 2007; Ulrich and Eppinger, 2012) nor in the Finite-Element Analysis (FEA) community, apart from a few works (see e.g. Leahey, 2003; Adams, 2006).

In order to ensure a correct and effective integration of the design analysis activity, several elements are necessary, such as an adequate design analysis process model, a suitable organisation, software and hardware, see (King et al., 2003) for a full framework. It is also important to have knowledge of the many factors that constrain and influence it. Several research works where factors that affect the engineering design situation or context have been surveyed have been done within engineering design, see e.g. (Hales, 1987; Hales and Gooch, 2004; Hubka and Eder, 1996, pp. 138ff). In this work, we focus on the description and the handling of the factors that particularly affect the design analysis. Specifically, we address factors that are exogenous to the design analysis activity itself but that have an important effect on it, that is, that can significantly affect analysis planning and that would negatively affect its execution and results if neglected. One example is the use of standard methods imposed on the analysis by a third party in a military equipment or an off-shore project: at the same time that it guides the design analysis activity it also constrains the degrees of freedom of the analyst. This paper presents a description of such factors and proposes a guideline for dealing with them — and acting upon them when possible — in a development project.

This guideline is first presented in the traditional setup of a developing enterprise that has its own analysis department. In many cases, however, analyses take place in alternative enterprise configurations where analysis is outsourced to engineering consulting companies (EC companies for short), or to suppliers in charge of the development of functions or components of the technical system. For these different enterprise configurations, the factors are affecting the analysis activity in different way. Alternative utilisations of the proposed guideline for a set of typical enterprise configurations are therefore also presented.

2 METHODOLOGY
The factors presented have been extracted from diverse sources. Some factors have been established from a series of interviews with Swedish manufacturing and consulting companies, where best practices could be observed. The interviewed persons in each company were generally responsible for performed design analyses activities, and in some of the companies also responsible for all of the product development departments. The complete interview approach is described in (Eriksson et al., 2013). Other factors have been taken from the literature. Because works on such an integration were found to be scarce, an extensive literature review was carried out (Motte et al., 2014). On the engineering design and product development side, the review is based on most ICED conferences proceedings (1985-2011), the ASME’s proceedings of the Conferences on Design Theory and Methodology (DTM), Design Automation Conferences (DAC) available to the authors (spanning from 1990 to 2011), the Journal of Engineering Design (1994-2011) and Research in Engineering Design (from 1989-2011). The design analysis review is mainly based on the proceedings of NAFEMS World Congresses (1999-2011), International Ansys Conferences (1987-2012) and Simulia Community Conferences (2007-2012), as well as the design analysis journals Finite Elements in Analysis and Design (1985-2012) and International Journal for Numerical Methods in Engineering (1985-2012).
The factors elicited are the ones that have been deemed to have the most influence on the analysis process. The list of these factors is also not meant to be exhaustive. The overall design analysis process model to which those factors apply is presented next.

3 THE DESIGN ANALYSIS PROCESS MODEL

Design analysis process models consist classically in three main design analysis activities: Analysis task clarification (step 1), Analysis task execution (step 2) and Analysis task completion (step 3). The Analysis task clarification activity consists of the identification of the design analysis task, followed by a step of preparation and adoption of a task content brief. Within the Analysis task execution activity the computational model is prepared (pre-processing), executed (processing) and the result accuracy is assessed. The design analysis task is completed in step 3 by interpreting and evaluating the established results and the computational model behaviour, and the outputs are integrated back into the project.

4 FACTORS INFLUENCING THE DESIGN ANALYSIS PROCESS MODEL

4.1 Overall model

The criterion held for qualifying an element as a factor influencing the process model is the following: an element exogenous to the design analysis activity but having an important effect on it. The factors significantly affecting the design analysis process are described below, grouped along their levels of influence: some appear at the development project (time, costs, etc.), some at the enterprise level, and some, such as legal aspects and standards, are outside the sphere of the enterprise. The factors are represented in Figure 1. Such a classification has the advantage of indicating what leverage a stakeholder can have upon them: the farther from the analysis activity context the more difficult it is to act upon those factors. That means that the influences from the factors at the project level can be more easily managed than the influences from the factors at the enterprise level. The factors at the environment level can almost never be acted upon at the design analysis level. Each of the factors is next described according to the level it belongs to.

4.2 At the environment level

The enterprise operates within a certain environment that constrains directly and indirectly the design analysis activity. The most important of those factors are the following:

- **Legal and environmental regulations**: The legal and environmental regulations to which the developing enterprise has to relate and that also set bounds for the design analysis activities. Note that this headline also includes products and systems which are protected under governmental laws regulating security issues, as well as those measures which are taken in individual enterprises in order to protect their products.

- **General industry and certifying standards**: The industry-gained experiences and knowledge together with certifying agency contributions are assembled in various forms of standards. These standards provide generally accepted methodology approaches, working procedures and means of assessing their accuracy. In many industrial branches, these standards must be followed, by injunction of the client (if EC company) or by certifying agencies.

- **Customer standards**: In some cases, the customers themselves have established standards that analysts must follow, in the format and extension agreed.

- **Hardware and software suppliers**: The capabilities (functionality, licences, training, etc.) offered by the hardware and software suppliers and the choices they make relative to further hardware and software development have a huge influence on the organization of the analysis department, and on the planning and execution of the design analysis activity.

4.3 At the enterprise level

The enterprise resources such as hardware, software and procedures and knowledge as well as the enterprise’s organisation, available competence and the quality assurance (QA) assessment all define the factors that at the enterprise level constrain the design analysis activities.

- **Hardware**: Appropriate hardware solutions such as desktop computers, computing clusters and grid computing environment allow for efficient execution.
Software: Certified in-house tools and commercial software are essential throughout the design analysis activities for an effective and consistent execution. Furthermore, software aimed at data and information management within project activities as well as for global enterprise accessibility are essential for successful integration of engineering design and design analysis processes.

Procedures and enterprise-stored knowledge: Presence of enterprise-stored knowledge allows for utilisation of relevant experiences gained from previous performed activities. Established procedures, based on the stored knowledge (through knowledge management), are important assets available to all stakeholders of the design analysis activities, thus providing guidance on how to conduct the analysis activities.

Organisation: The constitution of the enterprise organisation and its coordination mechanisms impact the way the design analysis activities are planned and executed. In particular, the separation distance, deeply correlated to the communication frequency between engineering designers and analysts, plays a very important role.

Employee competence: Adequate competence among analysts improves the likelihood of successful completion of the activities.

QA assessment: The aim of the QA assessment is to establish confidence in the performed work and subsequent interpretations of the results by the analyst, utilising methods such as verification & validation (V&V, ASME, 2006). The verification process consists of activities such as self-assessment performed by the analyst and planned quality checks, performed by another team member with appropriate competence, with the purpose of verifying that the computational model, assumptions and established results are accurate. The validation process consists of activities determining how well the performed work accurately models the real world.
4.4 At the project level

The product development project-related factors such as purpose and specifications of the design analysis activities, the level of concretisation of the product-to-be, and time and cost establish the frame in which design analysis activities are to be conducted. Furthermore, the monitoring of the process is an essential ingredient for the successful fulfilment of the task.

- **Overall purpose**: The overall purpose of the design analysis task is defined within the development project. There are several possible origins of the task and therefore several purposes. The initiation of the task can be connected with the evaluation of criteria within the product specifications, the assessment of a design proposal, or can be triggered by a re-design or a prior analysis. The purposes often include exploration of design, evaluation and verification of design solution proposals, contribution to improvements/modifications to the design, and support for the validation of the developed design.

- **Specifications**: The specifications constitute the description of what is to be analysed. Note that these specifications, derived from product specifications, are further elaborated and negotiated during the analysis task clarification.

- **Level of concretisation**: The possibility of, and need for, establishing various levels of detail of computational model and result is highly influenced by the level of concretisation (or abstraction) of the design to be analysed, for which the available data and analysis purpose differ.

- **Time**: A development project is based upon an often tight schedule. Analyses are connected to other project activities that depend on it or on which the design analysis activities themselves are dependent. Therefore a time constraint is often put onto the analysis task (not necessarily initially correlated to the time required by the task’s purpose).

- **Cost**: As in every development project, cost is an ever-present factor that must be taken into account. Costs obviously put restraints on the extent of the task as well as on what is achievable.

- **Process monitoring**: Continuous management, monitoring and communication to all relevant stakeholders throughout the activity allow for an adaptable process capable of handling imperative modifications to on-going tasks.

4.5 Example of influence of factors

The relationships both among the identified vital factors and with the design analysis process model are manifold. A couple of examples are selected to illustrate some common situations:

1. When a design analysis task is to be clarified (step 1), the product specifications should be formulated in design analysis terms, and the requested level of concretisation establishes guidance for selection of knowledge and software needed for analysis task execution (step 2). Furthermore, the selection of software and supporting hardware relates to the cost and time estimate requested by the product development project as well as the design analysis activity for setting the bounds of the execution. However, if an identified need requests knowledge or software not currently available within the enterprise, projects to establish this could be initiated or it could be acquired externally.

2. During design analysis execution, unexpected, overlooked or external environmental issues could emerge that have to be incorporated in the specifications; this could expand the purpose of the current task, redefine it or even trigger an additional design analysis activity.

3. Within the task completion of a design analysis activity (step 3), the level of information sent back to the project follows the description of the required outcome given in the specifications. The results assessment could also identify the need for improved development of V&V activities that can be formulated and implemented in the enterprise’s in-house tools (software) and procedures.

5 DEALING WITH THESE FACTORS IN A DEVELOPMENT PROJECT

These factors affect the analysis activity more or less during all the steps of the design analysis process model. Nevertheless, they are best dealt with during the analysis task clarification activity (step 1). First, it is important to notice that, although this is quite absent from the literature, many analysis activities are planned already from the product planning phase. Product planning is the phase where time, costs, resources, and risks linked to the subsequent product development project are assessed. Such an early planning of design analyses happens for example in cases where the product-to-be is already relatively detailed (incremental product development), when the enterprise has a detailed QA
program, etc. This aspect is crucial, because during product planning it is possible to act upon the factors at the enterprise level (see Section 4.3) so that when the analysis starts these factors do no longer act as constraints. The analysis task clarification moment is then usually revisited (step 1') before task execution and completion in order to agree on any adjustment relevant to the prepared task (see Figure 2a). When the analysis task clarification directly precedes its execution and completion (Figure 2b), it is no longer possible to act as widely at the enterprise level. It is risky to change the hardware system on such short notice, new software needs customisation and employees require training, etc. It is still possible, however, to act upon the project-related factors (see Section 4.4).

This section 5 gives recommendations for what can be done during product planning and product development. The factors at the environment level (regulations, standards…) can hardly be dealt with during a development project. They must be taken into account outside a development activity. It is therefore outside the scope of this paper and will only be touched upon in the last part of this section.

5.1 In product planning
This section describes how the factors at the enterprise level (described in Section 4.3) can be handled. This has been organized as follows: for each factor, a typical question or a set of questions regarding how to deal with the factor that influences the analysis is asked, and some of the influences are listed. The user (analyst or design analysis organisation) can systematically apply these to a given design analysis task.

- **Hardware**: What supporting hardware is suitable for analysing the identified design analysis activity? The lack of appropriate supporting hardware generally results in a need for investment in appropriate hardware environments; this in turn must be presented to the appropriate decision maker. Alternatively, the enterprise needs to cooperate externally to get access to the relevant hardware resources. It is possible during product planning to acquire the necessary hardware so that it is in place when the analysis is executed, whereas this is virtually impossible during product development.

- **Software**: What type of software is in place at the time of the design analysis activity? When adequate software is not present, investment in commercial software or development of in-house tools must be decided already during product planning, because the negotiation for commercial licenses and the programming and V&V activities of in-house tools takes time, as well as training and development of routines and procedures. During product development, the possibilities are much more limited, and it may be necessary to outsource the analysis task.

- **Procedures and stored knowledge**: What types of established procedures are in place at the time of design analysis activity? When procedures that are based on the common best knowledge as well as in-house expertise are not present, the description and development of appropriate procedures must be done a long time in advance.

- **Organisation**: What supporting organisation is available at the time of design analysis activity? Organisations where the different engineering disciplines are located closely together offer a more intuitive environment for information exchange. The constitution of the desired organisation of the project team should be presented before the product development project gets underway.

- **Employee competence**: What individual as well as combined competence level is available at the enterprise performing the design analysis activity? Inexperienced users need training and support from the enterprise. Note that another possibility is that experienced employees and experts (in-house or external) can serve as mentors for inexperienced colleagues throughout the duration of
design analysis activities, thus not only providing valuable support but also allowing for knowledge transfer to the inexperienced colleagues.

- **QA assessment**: How is QA assessed in the enterprise such that confidence is gained for approaches used and results achieved? The current capabilities of the enterprise V&V methods should be appraised during product planning; it will be necessary to establish confidence. If current V&V methods are found to be inadequate, appropriate measures must be taken.

5.2 **In product development**

This section describes how the factors at the project level (described in Section 4.4) can be handled.

- **Overall purpose**: What is the overall purpose of the design analysis task? The overall purpose should be weighed against the possibilities and limitations of currently available design analysis capabilities. If a discrepancy is found, it should be communicated in order to achieve an appropriate expectation regarding the outcome of the design analysis task.

- **Specifications**: How to handle the specifications at the start of the analysis? The specifications should by no means be accepted “as is”. The analyst might have limited knowledge about the design problem and need to discuss the relevance and accuracy of the specifications. (Petersson et al., 2012) discusses this aspect in greater detail.

- **Level of concretisation**: At which level of product concretisation is the design analysis activity involved? The design analysis activity must be carried out based on the available data and information, and the corresponding output results should be presented accordingly.

- **Time**: What time frame is set out for the design analysis task? The time frame should be selected such that it is efficiently connected to other project activities that are depending on it.

- **Cost**: What cost frame is set out for the design analysis activity? Before committing to the design analysis tasks, the cost frame has to be carefully examined and mutually agreed upon among all involved stakeholders. Relevant cost frame is important, as it is correlated to the success rate of the design analysis tasks.

- **Process monitoring**: How should process monitoring be carried out during the design analysis task? A well-planned process monitoring for all steps of the design analysis task is important for consistent, efficient and adaptable integration of the design analysis activity within the product development project. Thus, any new or updated information relevant to an on-going design analysis task should be communicated to relevant persons involved so that they have the possibility to act on and react to the impact that it might have on the design analysis task. Furthermore, if enterprise resources are modified at some stage of the design analysis process altering the initial time and cost frames, this should be conveyed to the project management so that adequate actions can be taken as soon as possible.

5.3 **Outside of a development project**

As mentioned above, the factors at the environment level (regulations and standards) can hardly be dealt with during a development project. If the enterprise wants to influence them, they need to take lobbying actions or participate actively in the development of those regulations and standards.

At the end of the project, another aspect of importance is that of capitalising the knowledge and experience acquired during the project. The endorsement from management on investment in resources and expertise knowledge for design analysis is vital (Adams, 2006). The core competence of employees performing the design analysis activities should continuously be addressed. The gained experiences and lessons learned through all design analysis activities should as far as practically and economically possible be elicited, formulated and stored as enterprise core competence for use in future projects (knowledge management). Without proper attention and control of employee competence and previous knowledge, the result could be erroneous decisions based on incorrectly established and evaluated computational models. Furthermore, it could lead to regression in effectiveness and competitiveness or even lack of trust in the design analysis activities if old errors are repeated.
6 DEALING WITH THESE FACTORS UNDER ALTERNATIVE ENTERPRISE CONFIGURATIONS

The in-house execution of design analysis activities at the developing enterprise (the company in charge of the development project) described in Figure 1 is the most unmitigated enterprise configuration, with full insight and control. Developing enterprises, however, do not always perform the analysis internally due to various reasons identified in the industry survey performed, such as lack of available resources and competences. Four additional enterprise configurations in which the design analysis activities are conducted have been identified. They are presented Section 6.1. Section 6.2 describes how to deal with the factors for each enterprise configuration.

6.1 Description of the alternative enterprise configurations

A first alternative enterprise configuration, displayed in Figure 3a, corresponds to the situation where resources for one or a selection of design analysis tasks are acquired externally (configuration a). The EC company merely provides the adequate resources for executing the tasks and the EC employee is assigned a workplace at the developing enterprise facilities utilising their resources. The EC company has the role of a staffing company. In the external execution configuration, displayed in Figure 3b, the design analysis activity is executed within facilities of the EC company with their available resources (configuration b). The communication and collaboration are primarily on a task level that aims at providing requested information on the project level. The enterprise configuration displayed in Figure 3c (configuration c) encompasses a broadening commitment in which the EC company and the developing enterprise have a closer and more in-depth cooperation, allowing for mutual understanding and commitments of investments in future demands on the design analysis activities. In this configuration the EC company is engaged to take full responsibility for the majority of (if not all) all design analysis activities within the developing enterprise. Finally, most products today are constructed of numerous more or less complex components and parts developed by various suppliers, as highlighted in the enterprise configuration displayed in Figure 3d (configuration d). These components need to be developed in parallel to the final product.

These different enterprise configurations are typical of common collaboration arrangements that are present in industry today. In practice, further decompositions into several layers of for instance suppliers, multiple external EC companies acting within a single development project and combinations of the configurations above are also common in industry.

6.2 How to deal with the factors for each enterprise configuration

Not all of the described enterprise configurations require their own design analysis process model or have specific factors. However, for each enterprise configuration, several of the described factors have different impacts in terms of organisation and effectiveness in planning, execution and arrangement of the analysis activity. The factors to specifically take into account for each enterprise configuration are discussed next.

In configuration a (external staffing analysis) cost and employee competence are the predominating factors in such an arrangement to take into account from the developing enterprise point of view. The time dedicated to the task, on the other hand, is a dominating factor from the EC company point of view in the sense that longer projects allow for reduced costs (due to less overheads). The analysis task execution in this form is more or less similar to the in-house configuration: the analyst works generally at the client’s office, allowing for natural communication with the project team, which possibly improves the analyst’s understanding of the product-to-be. On the other hand, the analyst can end up rather isolated, and does not benefit from the additional knowledge, competence and resources that reside at the EC company.

In configuration b (external outsourced analysis) the task identification and preparation of task mission (steps 1a and 1b) are often prepared within the developing enterprise and a request for a quote is sent for tendering to a selection of EC companies. Since the EC companies invited for tendering might not have insight into the developing enterprise’s standard procedures, the task content brief needs to be expanded. The level of detail expected in the analysis results interpretation (cf. step 3a), QA assessment, etc. (that is, most of the factors at the project and enterprise level), needs to explicitly be included in the task content brief. Reaching a task agreement generally requires a questions and answers session about the task mission for each EC company retained, which requires increased resources and expands the time and cost frames during task clarification. The EC company executes
the analysis tasks based on information provided by the developing enterprise as well as assigned analyst competence supported by stored internal knowledge and developed procedures originating from previous similar activities. These could also be beneficial for the developing enterprise since they might make use of these collective experiences gained outside their own enterprise. However, insights into the handling and control over their use are generally not controlled by the developing enterprise since it is proprietary information of the EC company, unless otherwise agreed. The developing enterprise does not necessarily need to have an organisation with competence suitable for task execution, but it should have an understanding of it so that the discussions around the task purpose and the specifications lead to a relevant analysis. An appropriate process monitoring must also be in place.

**Figure 3. Types of alternative enterprise configurations**

In configuration c (external partnership cooperation) many of the enterprise factors (hardware, software, employee competence, etc.) concern more or less only the EC company. The EC company is also more involved in the task clarification activity, providing the analyst’s perspective on the task identification and task mission preparation (steps 1a and 1b). The process monitoring and coordination of design analysis activities within certain projects can be left to the EC company. The core competences from both companies can be utilised to establish a common competence and knowledge foundation, with regards to design analysis activities, that will make both companies effective and successful in their common product development endeavours. The nature of the design analysis activities can also be oriented towards methodology and technology development for future design analysis demands, resulting in additions to established QA programs and procedures of the developing enterprise. Since the commitment between the developing enterprise and the EC company is part of a long-term perspective, the project level factors connected with cost and time are not as central for each individual project as in configurations a and b, but should be considered in a more holistic perspective. **Configuration d** (component or part supplier) is the most common configuration involving cooperation between developing companies. All documentation accompanying the delivery of the results (component or part) must be complete, self-explanatory and fully described, allowing unconditional approval from a QA assessment by the developing enterprise or by a third-party.
certifying agency. Essentially the companies perform two parallel projects (concurrent development of the whole product and of the component or part) that need continuous review and coordination on many levels. The enterprise factors affecting the operation at the supplier’s side need to be adapted to comply both with the expectations of the developing enterprise and with its internal business strategy.

7 CONCLUSION

This paper has presented a set of factors impacting the design analysis task during a development project and how to handle them adequately. It has also taken into account the different enterprise configurations in which the activities take place. Being aware of those factors should prevent fastidious iterations because of a poorly planned and organised task. This work also shows that analysis cannot be considered as a black box in the engineering design process — a lot of interactions between the analyst and the engineering designer are necessary. It is recommended to systematically apply these guidelines to enable successful integration of design analysis activities into product development.

These factors are assumed to be present whatever the size and complexity of the project and the presented guidelines are therefore deemed relevant both for large companies and for SMEs, even if these guidelines can be completed for specific organisations.

It is very difficult, if not impossible, to determine whether the presented set of factors is comprehensive or not, but one needs to focus on factors that have greatest impact on design analysis. In future work, these factors will be tested in an industrial setup monitoring an EC company collaborating with developing enterprises through various enterprise configurations.

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An integrative design analysis process model with considerations from quality assurance

Eriksson, M. & Motte, D.


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AN INTEGRATIVE DESIGN ANALYSIS PROCESS MODEL WITH CONSIDERATIONS FROM QUALITY ASSURANCE

Martin ERIKSSON, Damien MOTTE
Lund University, Sweden

ABSTRACT
Computer-based design analysis activities are an essential part of most product development projects in industry. An effective integration of the analysis activity into the product development process, especially when the design analysis is performed not by the engineering designer but by an analyst, internal or external to the company, is therefore very valuable. The contribution in this work is a design analysis process model that tries to eliminate some integration issues (transmission of incorrect information, disagreement on activities…) through the use of quality assurance techniques and procedures: quality checks, verification and validation, and uncertainty treatment. The process model is formulated in general terms so that it can be adapted to particular product development processes available in the industry.

Keywords: simulation, integrated product development, design process, design analysis

Contact:
Martin Eriksson
Division of Machine Design / Lund University
Department of Design Sciences LTH
Lund
SE-221 00
Sweden
martin.eriksson@mkon.lth.se
1 INTRODUCTION

In large and advanced development projects, computer-based design analyses of the design proposals (parts or whole products) are performed not by the engineering designers themselves but by analysts with adequate competence from the developing enterprise’s simulation department or by engineering consulting (EC) companies. This design analysis activity is an important asset to every product development project in industry because it permits an improved understanding of the physical system that is being developed. However, it also presents challenges if not planned and integrated into the engineering design process appropriately: if, for example, the goals of the analysis are not stated clearly, or if the analysis results are not efficiently controlled, the result could be time-consuming activities with an increase in design iteration loops. One way to deal appropriately with these challenges is to introduce quality assurance (QA) aspects in the classical design analysis process models. The QA approach tries to ensure that activities within a development project are fulfilling their goals, thereby increasing the probability for the whole project to be successful. Such an aspect is particularly important in the case of design analysis, where the data handled can be very sensible (in case of verification or validation of a design proposal) and miscommunications between the stakeholders are likely to occur. In order to improve the integration of the computer-based design analysis in the engineering design process with regards to the issues presented above, a design analysis process model that integrates different QA aspects is introduced. Especially, three QA aspects are emphasized. The first aspect is the use of quality checks (QC) of the analysis model, of the progress of the analysis solution processing, and of the analysis results that must be an integrative part of the design analysis process. The second concerns the growing demand of not only verifying the analysis process but also validating the analysis results. Such validation requires combining analysis with physical prototyping; this issue is typically addressed in the verification and validation (V&V) literature. Finally, it is increasingly required to communicate not just the result of the analysis but also both the confidence level of these results and the confidence level for the model. These three elements have been treated in the literature, but in a rather isolated way; cf. (Beattie, 1995) for QA, (Oberkampf et al., 2004; ASME, 2006) for V&V and (de Weck et al., 2007; Moens and Vandeputte, 2005) for uncertainties. Also, some works discuss the role of quality assurance in design analysis (Adams, 2003; Adams, 2006) but all these aspects have not been specifically integrated in the design analysis process models. Other QA aspects are also briefly touched upon, such as traceability and support for continuous improvement.

2 OVERALL APPROACH

The overall model of the design analysis process presented here is a synthesis of existing models that have been established in the finite-element analysis (FEA) and multibody simulation (MBS) communities, such as (Baguley and Hose, 1994; Adams and Askenazi, 1998; Erdman et al., 2001; Liu and Quek, 2003; Liu, 2003). The new elements are integrated in line with the corresponding literature but also according to best practices from industry and from personal experiences from the industry. The best practices from industry derive from a series of interviews, part of a larger project involving 14 Swedish manufacturing and engineering consulting companies, where these best practices could be observed. The people interviewed at each company were generally responsible for design analyses activities, and in some of the companies also responsible for the complete product development department. The complete interview approach is described in (Eriksson et al., 2013). The best practices coming from personal experiences are documented projects in the domains of automotive, marine, offshore and aerospace industries. Using such knowledge can be seen as problematic from a validity point of view. This knowledge may depend on the proponent who may lack hindsight in their limitations and have not been tested by third parties. On the other hand they are documented, used in different contexts, and the proponent has a deep knowledge of them, as they represent ten years of experience.

The presented model concerns mainly large-scaled projects (automotive industry, off-shore, defense). It can also be considered for smaller projects, but an additional number of elements need to be taken into account, such trade-offs between costs and efforts or competency availability, which are not investigated here.
3 QA IN DESIGN ANALYSIS – QC, V&V AND UNCERTAINTIES

A QA programme within a product development project can be said to aim at establishing a certain confidence level both in the future performance of the product-to-be (meeting the product specifications) and in the product development procedures utilized. The latter objective is coupled to the need to show the enterprise’s ability to meet product specifications, as well as to enable continuous improvement of the development process; cf. (ISO, 2008). The QA techniques and procedures of specific interest for the proposed design analysis process model are the so-called QC activities, V&V activities, and uncertainty treatment.

3.1 QC tasks
The QC tasks consist in using a set of tools and techniques in order to assure 1) establishing the required level of confidence in the produced results and 2) providing and documenting supplementary information as defined in the QA programme (such as “lessons learned” from the task). QCs are based either on self-assessment by the analyst, or on planned checks performed by the assigned resource within the project team with adequate competence. This person is often a senior engineer from either the developing enterprise or the EC company who has experience from past design analysis tasks or/and good knowledge about the product. The self-assessment tasks are intended to convince the analyst himself/herself that the analysis model, assumptions and established results are accurate.

3.2 V&V
V&V has not originally been developed with QA in mind, but its purposes fit very well those of QAs and make it an essential part of the QA programme for product development projects that rely heavily on design analysis activities. V&V 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. This assessment is primarily made through comparisons with known solutions if available. In situations where no known solutions are available, the comparisons are usually performed with comparison to an alternative modeling approach. 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. While the QC tasks rely primarily on the experience of the analyst or assigned persons and one’s own judgment, V&V is more oriented to an “objective confidence” (cf. ISO, 2005) in the design analysis procedures and results. The V&V activities are therefore two cornerstones when establishing confidence in the predictive capability of a design analysis activity. The process of verification and validation must clearly be adapted to each particular development situation, where available information and uncertainty in the utilized input variables and models are considered and outlined in the activity description. Note that the term “verification” here applies to the computational model, while verification in QA is defined as the confirmation that the product specifications have been fulfilled (ISO, 2005).

3.3 Uncertainties
From an engineering point of view, uncertainty is present in all areas of design (products, processes, users and organisations). New designs have parameters and behaviours not known completely beforehand, processes have uncertain durations and uncertain effects, users can change and organisations can change and, more widely, contexts, environments, and long-term conditions of use are unpredictable. Usually, input data and results are in the form of point-value estimates, and uncertainties are not taken into account in the planning, execution and completion of a design analysis activity either than by introducing safety factors on adequate parameters and measures. Taking uncertainties into account, however, permits better control and confidence in the analysis results, and is therefore an essential element of QA. 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). Uncertainty is represented by a relationship (or a function) that expresses the degree of evidence (likelihood, belief, plausibility, etc.) that the true results are in the defined set. In the majority of published literature and practically utilized approaches towards the modeling of uncertainty within design analysis, we find probability theory, evidence theory, possibility theory, fuzzy set theory and interval based theory (Helton, 2004). The propagation of uncertainty throughout the design analyses task are often studied though the Monte Carlo simulation approach where a number of analyses are performed to represent the distributions of the variables being studied. However, in some situations design parameters are described in vague terms or in linguistic terms that are hard to represent by i.e. probability distributions. Furthermore, when studying a system with a high level of epistemic uncertainties, the possibility of characterizing them with precise probability distributions becomes more challenging from a practical point of view. And, as discussed for instance in (Helton et al., 2004), there is currently no clear consensus among researchers about the statistical foundation and the practical benefits of introducing the alternative uncertainty theories mentioned above (evidence theory, possibility theory, etc.) within simulations performed today. The main reason stated in (Helton et al., 2004) is that the Monte Carlo procedures for establishing uncertainty representation for the other uncertainty theories are prohibitively expensive from a practical computational perspective unless combined with variance reduction techniques with the dual purpose of reduce computational cost of a sample run and to increase accuracy using the same number of runs (see Choi et al., 2007 for such methods as Latin hypercube and stratified sampling methods). The analysis model can be greatly enriched when uncertainties are quantified and included in the analysis activity. By knowing the uncertainties linked to a given design analysis task, resources can be allocated adequately and the prediction and interpretation of the results can be enhanced. Understanding of uncertainties, together with techniques for characterising, aggregating and propagating them throughout the design analysis activities, are important for providing insights to establish confidence in the decisions based on the uncertainty presentation established from the design analysis task outcome.

4 OVERALL DESIGN ANALYSIS PROCESS MODEL

The overall design analysis process model that is used as a basis for introducing the QA elements is presented in Figure 1. It consists in the three main activities, Analysis task clarification, Analysis task execution and Analysis task completion of the design analysis activity that are displayed in Figure 1 together with their corresponding steps. The analysis task clarification (step 1) consists of the three steps as outlined next. In the identification of the task (step 1a), the objective is to ascertain the task relevance and need for design analysis activity. A pre-analysis assessment is often performed to get an indication of appropriate software and hardware resources, expected input, requested output, other resource demands and cost and duration. A preliminary mission statement is written in which the relevance of the task is emphasized. Once the relevance of the task has been agreed upon, the preparation of the task content brief takes place (Step 1b). The aim of the last step in the task clarification activity, planning and agreement of the task (step 1c), is to reach a mutual understanding and agreement about the task ahead. Within the analysis task execution activity (step 2) the agreed task is further processed and the computational model is prepared for solution processing in the pre-processing step (step 2a). After solutions have been established in the solution processing (step 2b), the analyses are verified and the result accuracy is assessed (post-processing, step 2c).

1. Analysis task clarification
   1a. Identification of the task
   1b. Preparation of the task content brief
   1c. Planning and agreement of the task

2. Analysis task execution
   2a. Pre-processing
   2b. Solution processing
   2c. Post-processing

3. Analysis task completion
   3a. Results interpretation and evaluation
   3b. Documentation and communication
   3c. Integration of the results into the project
   3d. At enterprise level, documentation and internalization of acquired knowledge from the analysis task

Figure 1. Overall design analysis process model with defined activities and steps.
Interpreting and evaluating the established results and the model behaviour (results interpretation and evaluation, step 3a) complete the design analysis task, and the output are integrated back into the project (documentation and communication and integration of the results into the project, steps 3b and 3c). The elicited analysis information and experiences gained are then also communicated to the enterprise for inclusion in the enterprise core knowledge system for allowing continuous improvement (documentation and internalization of acquired knowledge from the analysis task, step 3d).

4.1 Analysis task clarification
The analysis task clarification activity is as important as the analysis execution itself, because it is at that stage that all specifications that will need to be quality-assessed are established and agreed upon. The following elements must be taken into account for the preparation of the design analysis brief in a QA perspective (they are also listed Figure 2):

- The statement of the analysis purpose and goal(s) is essential and must be discussed thoroughly. It has been reported in the interviews that incomplete descriptions had led to costly and undesirable re-analysis. A typical example is the formulation of a brief for a solution evaluation that lacked any request for recommendations for further design improvements if the design solution is proved unsatisfactory.

- The specifications are often categorized as wishes or demands. Regarding demands, it is important that they are discussed thoroughly. For instance, if a structural component is only allowed to locally experience plasticity, then the term ‘locally’ needs to be further elaborated to explain how it should be interpreted based on the selected choice of resources, software and level of concretization in the current analysis. Sometimes, during negotiations, it is possible to give a range or set of values instead of a point-value estimate for a specification.

- The different categories of uncertainties connected with the specifications should be identified and described in the task content brief, as well as the techniques to characterise and aggregate (combine) them for propagation in the later design analysis activities, for example design of experiments (DOE) and probabilistic models. It is important to establish the modalities of task monitoring, results communication and follow-up of the task activity.

- The content and extent of the QC and V&V activities, methods and tools have to be defined. The expected level of confidence in the results of each of these activities must be established.

- The requested level and format of traceability of the performed activities should also be defined. This will serve as an effective way of finding potential alternative solution candidates later on in the projects if product specifications are altered for some reason. Furthermore, it will serve as a good basis for future projects with similar specifications (continuous improvement).

- The description of how the analysis results will be used and integrated within the project is a valuable part of the mission statement as it can significantly affect the further planning and execution of the tasks and communication of the results. The form of the deliverables must also be carefully specified. They can be in the form of plain data, but generally a more elaborated interpretation and conclusion of the performed activity is preferable. Without this proper description, the information delivered during the execution and at the completion of the task might be inconclusive.

- The task content brief should contain enough details to enable a decision for commitment to carry out the task. The presence of possible model representations should be considered together with description of alternative approaches for carrying out the task.

In order to increase the assurance that the brief will be comprehensive, it is important that all the stakeholders have the possibility to influence its formulation. The analysis-specific knowledge and expertise is not always apparent for other stakeholders in the project and should thus be provided throughout the planning of the task. This means that in general, the brief will not be complete or even correct unless the analysts are given the opportunity to comment on it and the project manager, the engineering designers as well as other project team members need to be open for discussion. It has been chosen to separate the step of preparation of the task content brief (step 1b) from the step of planning and agreement of the task (step 1c) for two main reasons. First, the planning of the task can be done so as to fit with the concurrent product development activities. Second, there can be a certain period of time between the preparation step and the moment the decision makers finally agrees on the task, which may lead to final changes and discussion before the brief is finally accepted. Once all
items in the brief are in place, the analysis activity should be carefully planned and a formal document should be prepared and mutually agreed on between the analyst and the project leader that forms the basis for the analysis execution (step 1c). In the case the parties cannot agree, it may be necessary to re-iterate step 1b and 1c. As described above, it is very important not to proceed further with the design analysis task without a proper description of agreed monitoring activities, intermediate milestones and checkpoints, since this will introduce many uncertainties and problems that might endanger not only the success of the design analysis activity but also the complete project realization.

1a. Identification of the task
- Discussion around task relevance between project leader, analyst(s) and client
- Decision to perform an analysis

1b. Preparation of the task content brief
- Enterprise- and project-specific elements
- Clarification of the task
- Overall purpose of the task
- Specification description
- Resources and procedures
- Time and cost frames
- Level of concretisation
- Determination of deliverables
- Standards and regulations
- Modalities of
  - task monitoring
  - follow up
  - results communication
- QA confidence level assessment
- Traceability
- Uncertainty description

1c. Planning and agreement of the task
- Discussion and agreement of the analysis task brief
- Contract between analyst leader and project leader

Figure 2. Analysis task clarification steps

4.2 Analysis task execution
During the pre-processing (step 2a) of the analysis task execution (see Figure 3), the agreed task content brief is treated further and the actual computational model for solution finding is prepared that is utilized in the solution processing (step 2b). The established results are reviewed within the post-processing (step 2c) with the purpose of providing adequate understanding of the results. Furthermore, standard design analysis assumptions should be applied that correspond to the requested results delivery and the solution approach selected. Material properties, idealizations i.e. beams and shells in finite element method (FEM), discretization i.e. mesh density in FEM, cell density in computational fluid dynamics (CFD), initial and boundary conditions and loading are among the assumptions always connected to a design analysis activity.

2a. Pre-processing
- Task content compilation
- Solution approach
- Appropriate assumptions (material properties, idealizations, discretization, initial and boundary conditions and loading)
- Result definition

Quality tasks
- QC of the computational model (see Figure 4)
- Model uncertainty aggregation
- Tracking of the task in engineering data management (EDM)

2b. Solution processing
- Solution scrutinizing

Quality tasks
- Progress monitoring
- QC intermediate results (see Figure 4)
- Analysis uncertainty propagation
- Tracking of the task in EDM

2c. Post-processing
- Result review

Quality tasks
- V&V: analysis verification to assess accuracy
- QC of established results (see Figure 4)
- Analysis uncertainty assessment
- Tracking of the task in EDM

Figure 3. Analysis task execution steps
Pre-processing (step 2a) involves many aspects starting from defining a representative engineering model (such as a geometrical CAD model or a functional model) that forms the basis for establishing the computational design analysis model. The requested results to be elicited, delivered and monitored during the solution processing should be assessed together with the computational model description. Solution processing (step 2b) needs to be executed in a way that allows for intermediate results, analysis status and areas of concerns to be communicated to all relevant stakeholders within the project and enterprise, as displayed in Figure 4. This is important to have a flexible and adaptable process in order to be able to use and provide most recent information, such as results to connected activities at any given time during the task continuation. This furthermore gives feedback on the status of the task to the project manager with regards to expected deliveries that might call for updates of planning of not only the current activity but also other dependent or connected activities within the project. A tracking procedure of all analysis activities, utilizing either simple Excel worksheets or an advanced engineering database management (EDM) system, should be established if not already available and then continuously updated in order to provide traceability of the analysis.

The established computational model together with intermediate as well as final results should be quality-checked in order to judge the appropriateness of the established model and assumptions made with regards to the overall QA framework at the enterprise, the project decisions and the defined task content brief. The outcome of the QC check is important feedback to the project team since any relevant and required additions and modifications to the on-going task will be captured, updated and communicated at appropriate point in time of the task continuation. (see also Figure 4). This will reduce the risk of providing irrelevant results as well as utilizing unnecessary time and resources. In the case the QC activity renders in required updates to the computational model, performed analysis or established results, it may be necessary to re-iterate one or more of the execution steps.

The established results within the post-processing (step 2c) should be reviewed by listing, displaying contour plots, and animating of various overall results. This should be done with the purpose to make judgement and provide understanding of the general model behaviour, to the extent that verification (V&V) of model accuracy and convergence in the established results can be performed. The listing should consist of output information from solution processing such as error and warning messages along with the analysis results of interest. Studying the reaction forces from the system and comparing them to applied loads is one part of the accuracy assessment. Any discontinuity at locations where they are not expected to be is a sign of inconsistent accuracy, and improvement in discretization might be needed. Unexpected and irrelevant occurrences of high local results should be viewed and judged as real or spurious. All of the above are part of the self-assessment (sanity check of established results) to be performed by the analysts that together with planned checks of the established results is part of the QC activities ensuring the verification of the model accuracy.

The identified uncertainties should be aggregated based on definitions set up in the task content brief and modelling of the selected approach for uncertainty propagation should be defined. Furthermore, the confidence level of the established results should be also be assessed in terms of planned quality

Figure 4. Solution processing step task monitoring and quality checking
check and established means of additional required verification activity to ascertain that the computerized model provides expected results under the given assumptions. The analyst should make use of the most suitable form of investigating the influence of uncertainty on established results. Sensitivity analysis and tolerance studies are often performed to assess this from an engineering viewpoint. Also approaches such as DOE are used when the analysis is to be performed on limited information regarding the product-to-be. DOE is one of the frequently used approaches within physical experimentation to study and extract vital variables among the studied variables. It is also applicable within design analysis since each deterministic analysis can be seen as a virtual test under a given experimental condition. Also, since the category of uncertainty traditionally addressed within analysis is of an aleatory nature, it is not that surprising that probability theory methods are employed. During post-processing the approach selected for investigating the influence of uncertainty should be quality checked and verified like any other analysis task performed. With a quality checked and verified analysis, specific results can be extracted and stored for further handling in the completion stage of the design analysis activity.

4.3 Analysis task completion

The analysis task completion consists of four steps, namely results interpretation and evaluation (step 3a), documentation and communication at the project level (step 3b), integration of the results into the project (step 3c) and at the enterprise level, documentation and internalization of acquired experiences from the analysis task (step 3d) as displayed in Figure 6. These are discussed in turn.

The results interpretation (step 3a) relates to the interpretation by the analyst of all relevant data and information that can be drawn from the analysis task execution. During that step, the validation activity should be performed (if agreed), the influence of uncertainty on extracted results be quantified and the whole step be quality-checked. These three activities are described in turn below.

Validation. A physical test (representing the validation domain) should be conducted with to correlate design analysis data (analysis domain) and it serves as the primary source of validation as displayed in Figure 5. It needs careful planning and it should in the best of circumstances allow for multiple data measures that ascertain that various analysis assumptions all provide a holistic representation within the complete use domain as displayed in Figure 5a. In situations where the validation is planned to make use of an existing physical test configuration representing a validation domain that does not fully encompass the analysis and use domains, the correlation needs to be carefully performed and the prediction outside the boundaries should be utilized with care. Correlation and validation of the analysis results against experimental test data are generally complicated, and the evidence for the correlations between the analysis and validation domains can be of varying degrees, from single-point values (showing trends) to advanced probabilistic models of the overlapping areas of both domains.

As can be noticed, in this model the validation part of the V&V belongs to the completion activity, while the verification part belongs to the execution activity. This is because verification deals with the computational model while validation deals with whether the results from the analysis models accurately represent real-world conditions.
Uncertainty quantification should also be used as an input to the validation activity so that the relationships between the various domains in Figure 5 are covered to the desired extent. The uncertainty connected with the physical experiment (representing the validation domain) should be assessed such that the uncertainty in the correlation of the analysis domain results to the validation domain measures can be quantified and documented. With this information in hand there is a possibility to judge the product’s ability to cope with the uncertainties identified within the use domain, which they were intended to describe in the first place.

**Quality checks.** Quality checks of the conclusions drawn in the results interpretation, and of the validation activity, should be conducted by the resources appointed responsible for QC. In *documentation and communication* (step 3b), the extracted information and conclusions drawn are documented and communicated at the project level. Also the quantification of uncertainty should be represented in the documentation. The established documentation should be checked for conformity (by both the analyst and the resource responsible for QC) to the defined purpose in the content brief and to ascertain that all findings and conclusions in previous sub activities are correctly reproduced within the documentation. The final documentation should be communicated to all stakeholders of the current project in agreed appropriate channels and formats for decisions on subsequent actions, allowing for integration in the project (step 3c); this is especially important in the case where the analysis is made by an EC company. Additional improvement proposals should also be prepared and documented with the goal of establishing an increased amount of essential data and information valuable for making accurate conclusions and decisions within the project on the effect on the product studied.

In *integration of the results into the project* (step 3c), the output is integrated back into the project, and the results are taken up in the project decision procedures, and they form the basis for potential further analyses. The findings in the QC and validation activities during post-processing also provide feedback on the confidence level of the performed work and conclusions drawn from it. The outcome of any incorporated uncertainties in a design analysis activity need to be integrated in the decision activities within the product design process.

Finally *at the enterprise level, documentation and internalization of acquired experiences from the analysis task* (step 3d), the established data and information elicited should be stored and handled within the enterprise in a systematic manner that facilitates decision support for future product development projects and product generations. Also, the experience gained should be formulated such that lessons learned that serve as basis for best practice development as well potential improvements in current practices and tools will become available not only for the project members but for the whole enterprise.

### Figure 6. Task completion steps

#### 3a. Results interpretation and evaluation
- Results interpretation
- Quality tasks
  - V&V: analysis validation to assess correspondence of results with intended use
  - QC of the results interpretation and of validation (see Figure 4)
  - Uncertainty quantification

#### 3b. Documentation and communication
- Task documentation
- Additional improvement proposals documentation
- Uncertainty representation
- Task communication
- Quality tasks
  - QC of the documentation (see Figure 4)

#### 3c. Integration of the results into the project
- Implementation of Task results and findings
- Participation in decisions
- Contribution to further analysis

#### 3d. At enterprise level, documentation and internalization of acquired experiences from the analysis task (also part of QA)

### 5 CONCLUSION

The contribution in this work is an enhanced design analysis process model that implements several QA aspects such as QC, V&V and uncertainties, allowing for a better integration of the design analysis activity in the overall engineering design process. The last two elements are typically not systematically integrated in the design analysis process. An interesting result of this process modelling
is that verification and validation are not directly coupled, although they are always presented as associated in the literature. The model proposes a large array of recommendations and activities that can seem overwhelming at first but are necessary for large development projects. This model can also be used as a checklist for smaller projects with the reservations stated Section 2. The model has been formulated as much as possible in general terms so that it can be adapted to many product development processes available in industry.

Although design analysis is mainly used for evaluation, this model is intended to be also used for alternative design analysis tasks, such as explorative studies, support activity to physical testing or investigations of the use domain (cf. Figure 5). In future work, the QA aspects will be tested in an industrial setup monitoring selected projects of varying complexity within an EC company collaborating with developing enterprises.

REFERENCES


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

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

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. Ehrlen-spiel [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 fi-
nite 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 permeates 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

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

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 *management 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 performing 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 de-
signers and for one of the companies where analysts and designers were the same person, some guidelines or some form of documents describes the activity.

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.

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 men-
tioned 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.

<table>
<thead>
<tr>
<th>Sources of information during execution</th>
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<tr>
<td>Best practices documents</td>
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<tr>
<td>Corporate networks</td>
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<tr>
<td>Conferences</td>
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<td>Department forums</td>
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<td>Internet user groups</td>
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<td>Literature surveys</td>
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<td>Mentorship</td>
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<td>Organizations and universities</td>
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<td>Software support</td>
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<th>Verification of performed analysis</th>
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<td>Analysts responsibility</td>
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<td>Review by colleagues</td>
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<td>Review by stakeholders</td>
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<td>Sanity checks</td>
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<td>Use of validated methods</td>
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<th>Validation of performed analysis</th>
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<td>Field test</td>
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<tr>
<td>Method test</td>
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<td>Old reports</td>
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<td>Physical test</td>
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**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 parameters 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.

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**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 gives 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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References

Martin Eriksson
PhD Student
Lund University, Department of Machine Design LTH
P.O. Box 118, 221 00 Lund, Sweden
+46 (0) 46 222 85 11
+46 (0) 46 222 80 60
martin.eriksson@mkon.lth.se
www.mkon.lth.se
Integration of the computer-based design analysis activity in the engineering design process – a literature survey

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


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

Damien Motte  
Division of Machine Design LTH  
Lund University  
Sweden  
damien.motte@mkon.lth.se

Martin Eriksson  
Division of Machine Design LTH  
Lund University  
Sweden  
martin.eriksson@mkon.lth.se

Håkan Petersson  
School of Business and Engineering  
Halmstad University  
Sweden  
hakan.petersson@hh.se

Robert Bjärnemo  
Division of Machine Design LTH  
Lund University  
Sweden  
robert.bjarnemo@mkon.lth.se

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 fulfills 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.


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%.

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).

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 engineers 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;87;68;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, delimitmed, 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 compa-
ties, 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
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 situ-
lations 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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INTEGRATION OF DESIGN ANALYSIS IN THE DESIGN PROCESS - A LITERATURE SURVEY


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Eriksson, M.

ABSTRACT
From an engineering point of view, uncertainty is present in all areas of design (products, processes and organizations). Computer-based design analysis, here confined to quantitative computer-based structural design analysis within mechanical engineering, serves as an important source of information in decisions taken during the design activity; importantly, it aims at giving confidence in critical design results. It is moreover nowadays used on all levels of concretization of the product-to-be throughout the development process. It must therefore address different uncertainties and errors during the whole development process. To that end, the concept of predictive design analysis (PDA) was introduced. The initial version of PDA treated primarily uncertainties of aleatory nature and was confined to product/technology-related issues. Today a broader perspective on the uncertainties is needed, and it is important to develop reliable design analysis methods because of the increasing use of design analysis by both analysts and engineering designers. Hence it is therefore necessary to extend the PDA framework into a full-blown methodology. PDA is a specific computer-based design analysis methodology that supports the systematic handling of uncertainties and errors during the computer-based design analysis activity throughout the whole development of the artifact. Such a methodology includes: Not only aleatory uncertainties, but also epistemic uncertainties connected with factors affecting the design analysis activities; Operationally efficient and effective integration between the engineering design and design analysis activities; Quality assurance aspects in terms of quality checks, verification and validation activities taking physical testing into account; Progress monitoring throughout all design analysis activities from clarification to completion; Traceability in utilized information, technologies and established results; Information and knowledge re-use for an improved uncertainty treatment in future design analysis activities through establishment of lessons learned and best practice documentation as well as methodology development.

INTRODUCTION
Uncertainties and errors have always been present in the development of a product, be it a completely new product or variant design or re-design where some form of previous knowledge is available. For new designs, parameters and behaviors are not known completely beforehand, processes have uncertain durations and uncertain effects, conditions of use can change and, more broadly, contexts, environments, and long-term conditions of use are unpredictable [1]. Regarding variant design or re-design, a component or system developed for a particular context might not work as well in a new environment with slightly different requirements.

Computer-based design analysis is instrumental in the handling of uncertainties during the engineering design activity. Typically, computer-based design analysis — considered in terms of quantitative simulations of physical phenomena found in engineering practice that are computationally solvable with
current state of the art computer-aided engineering (CAE) software tools — aims at evaluating design proposals and at reducing the need for physical prototyping. It serves also as an important source of information in decisions taken during the engineering design activity; importantly, it aims at giving confidence in critical design results. In other words, it helps the engineering designer to get a grip on the different uncertainties related to the product.

Traditionally, computer-based design analysis process models and techniques [2-5] do not deal explicitly with uncertainties but use safety factors which are often found in various engineering standards. Even if this way of working is still used today and is in many cases justified, there has been a growing interest in taking into account uncertainties in a more systematic manner. In the late 90s the concept of predictive design analysis (PDA) was introduced [6;7]. Early works mainly focused on uncertainties related to the model inputs (e.g. loads and boundary conditions) and numerical simulation (e.g. discretization error, programming errors); see Marczewski [8]. In consequence, statistical and stochastic methods and techniques (design of experiment, DOE, Monte Carlo simulations) have been applied to computer-based design analysis.

However, these uncertainties are not the only uncertainties present in design analysis. Other types of uncertainties related to the project, company or environment need to be taken into account. These uncertainties also should be handled differently depending on when, during the development process, these analysis activities occur. It is not enough either to just “take uncertainties into account”, it is also necessary that they be effectively handled and errors minimized, and that lessons learned are exploited.

All these elements indicate the need for an extension of the PDA framework. This paper presents such an extended PDA methodology and is organized as follows. In the first part, different concepts of uncertainties and errors are introduced. Second, how the methodology has been developed is explained. Third, the methodology itself is presented. Finally, one case study is presented.

In the scope of this paper, the PDA methodology has mainly been applied to finite element analysis (FEA) based on computational structural mechanics (CSM) simulations. However, the same issues related to uncertainties and errors are present for other design analysis areas such as computational fluid dynamics (CFD) and multibody simulation (MBS), even if their treatments at the detailed level differ, due to the specificities of each area.

UNCERTAINTIES AND ERRORS
The first part of this section defines and characterizes uncertainties and errors. The second part presents the sources of uncertainties and errors concerning the design analysis model inputs and the numerical simulation itself (the endogenous uncertainties and errors) as well as the other categories of uncertainties that affect the design analysis activities (exogenous uncertainties and errors).

Definition and characterization of uncertainty
There are many ways of defining uncertainties, depending on the field and purpose of study [9]. In this context, the definition used in Hastings and McManus’ framework [10] is chosen: “Uncertainties are things that are not known, or known only imprecisely.” An important aspect of this definition is that uncertainties can be associated either to a risk or to an opportunity. Risk is an undesirable resolution of an uncertainty. Opportunity, on the other hand might exist if an uncertainty is resolved in a way favorable to the system. While most works within PDA deal with uncertainty to mitigate risks, it is important to have in mind that PDA can be used to exploit uncertainties.

In the literature different categorizations and representations of the concept of uncertainty exist, see e.g. [1;9;11;12]. Within these works two approaches to categorization of uncertainties are often mentioned: categorization based on the nature of the uncertainty and categorization based on the sources of the uncertainty. In the “nature of the uncertainty” approach uncertainties are divided into two major categories namely aleatory and epistemic [9].

- **Aleatory uncertainty** is used to describe the inherent variation associated with a physical system or product and also with the measuring devices utilized to monitor it. As stated in [12, p. 14], Aleatory uncertainties are “randomly distributed quantities that can take on values in an established or known range, but for which the exact value will vary by chance from unit to unit or from time to time”. The variation inherent in the environment in which the system is acting also belongs to the aleatory category of uncertainties. Aleatory originates from the Latin alea or aleatorius meaning throwing the dice. In the literature this category of uncertainty is sometimes also referred to as variability, irreducible uncertainty, inherent uncertainty and stochastic uncertainty [13, p. 336].

- **Epistemic uncertainty**, originating from the Greek episteme meaning knowledge, on the other hand is used to describe the possible lack of information or knowledge that is derived from some level of ignorance of the system or environment or in any activities and phases involved in performing the modeling and analysis or simulation [12]. The term “possible lack of information” used above implies that epistemic uncertainty fundamentally deals with incomplete information that could be due to vagueness, or to nonspecific information or dissonance (conflicting information) [13]. The epistemic uncertainty is also referred to in literature as reducible uncertainty, subjective uncertainty, model form uncertainty and cognitive uncertainty [13, p. 336]. Improved quality and availability of data and/or information will reduce the uncertainty in the epistemic uncertainty and also in the prediction of a given system.

The handling of uncertainties strongly connects to the present state of knowledge of the design properties as displayed in Figure 1, taken from [9]. The top picture in Figure 1 shows the possibility of improving the present state of knowledge by reducing the uncertainty. However, since the uncertainty consists of both epistemic uncertainty, which is reducible, and

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aleatory uncertainty, which is irreducible, an analysis outcome will always be bounded by some degree of uncertainty as highlighted in the bottom picture in Figure 1.

This differentiation is operationally important, as the uncertainties endogenous to the design analysis are mainly aleatory, while the uncertainties linked with product development are often epistemic. Monitoring and managing them during the analysis activity provides the possibility of mitigating actions for reducing the uncertainties.

Figure 1. Illustration of uncertainty with regards to knowledge.

Definition and characterization of the errors

The categorization of uncertainty above addresses the deficiencies in analysis models that are due to lack of knowledge. However, another source of potential deficiency in the outcome of the analysis models utilized is the errors associated with design analysis. The errors are defined as identifiable inaccuracies in any of the activities and phases of the modeling and execution of the analysis model that are not due to lack of knowledge [13]. In the literature, different categorizations and interpretations of error are presented, such as acknowledged and unacknowledged or intentional and blind errors. The following categorization has been chosen (see [13] for further reading):

- **Acknowledged errors** are inaccuracies identifiable by the analysts.
- **Unacknowledged errors** are not identifiable by the analysts but are identifiable by other stakeholders.

The acknowledged errors can originate from decisions regarding the design analysis at hand, such as the comprehensiveness of the analysis model regarding the reality which it imitates, or restrictions on development resources. Thus the acknowledged errors are of such nature that the outcome of the analysis depends on them, and they should be given attention during review and monitoring of the outcome. The second category of errors, which do not depend on a deliberate decision, are such errors that are categorized as unacknowledged errors, which are built into an analysis model without the knowledge of the analyst. This category of errors is much harder to estimate and evaluate in the review and monitoring processes of the analysis outcome, since the analyst is usually not aware of the extent to which these errors exist in the current model and the dependence of the outcome on them. External knowledge and previous experience could serve as important sources of information when investigating the existence of unacknowledged errors as well as how to assess them.

Sources of uncertainties and errors within design analysis

When performing design analysis, a number of uncertainties and errors concerning physics and numerical simulation techniques have to be considered. In general terms, the analyses are often referred to some level of complexity that relates to dependency on a response to different variables and uncertainties [14]. Marczyk [8], among others, has summarized these uncertainties and errors into a few categories:

- Loads (static, dynamic, impacts, etc.)
- Boundary and initial conditions (stiffness of support, velocities, etc.)
- Material properties (stress-strain data, density, imperfections, etc.)
- Geometry (shape, assembly tolerances, etc.)
- Modeling uncertainty (level of abstraction, lack of knowledge, etc.)
- Mathematical uncertainty (accuracy of the model)
- Discretization error (discretization of the boundary conditions, etc.)
- Programming errors in the code used
- Numerical solution errors (round off, etc.)

The first four categories concern physics, and the other five categories deal with numerical simulation. Thus, the level of accuracy of the response is highly dependent on the input data and the design analysis techniques used. [14]

These uncertainties can be aleatory and epistemic. From an industry survey within Swedish industry [15] it was found that epistemic uncertainties were often connected to load and boundary conditions, material data regarding damping and fatigue characteristics.

Sources of uncertainties and errors within product development

Besides inputs and simulation-related uncertainties, there are many other factors that affect the design analysis outcome greatly, for example the employees’ competencies, or new regulations. These modify the way the design analysis is planned and executed, or the way the results are communicated. This section presents a brief review of various sources of uncertainties. Within product development the sources of uncertainties are manifold and can be found in many various contexts as outlined in e.g. [16,17]. The classification according to [16] is displayed in Figure 2. The uncertainties within the system boundary can be influenced by the engineer(s) and also the company to a greater extent than those outside the box.
Figure 2. Sources of uncertainty according to [16].

Many sources of uncertainties are outside a company’s direct control and arise in the use, market and political and cultural contexts as highlighted in Figure 2. The intended environment in which the product is to be utilized can be changed by users, thus requiring a reliable product in different environments. The user’s skills also introduce uncertainties. A less competent user might do the wrong things or not fully comply with the instructions. On the other hand a skilled user might use the product to the extreme and beyond, utilizing it for tasks that it is not designed for. Of course the market as well as the political and cultural contexts carry large numbers of uncertainties that are hard to identify and mitigate or exploit in the development of a product. The nature and the expected lifespan of a product will affect the sensitivity of the product to rapid changes. With products designed for fast moving/changing markets as in the mobile phone industry, these aspects are well known and thus receive attention. In other industries, with long life spans such as aerospace, products are not as sensitive to market changes. However, a sudden change in the political or cultural context such as 9/11 can have a dramatic impact on the industry.

DEVELOPMENT OF THE METHODOLOGY

The methodology presented is the result of 15 years of development. The first efforts concerned the inclusion of the endogenous uncertainties into the design analysis process and the adaptation of statistical and stochastic methods for this purpose, while taking into account the specificities of the different phases of the engineering design process [6;7;14]. Work has progressed slowly to include other epistemic uncertainties [18], an operational process model [19], method development [20] and quality assurance (QA) aspects [21].

The bases used to build the methodology have been various literature studies in 2003 and 2013 [14;22], an industry survey in 2008-2009 [15], and several industrial projects that have helped illuminate the need for such a methodology and enriched it.

Literature studies

An initial literature study was performed in 2003 [14]. It covered the tools and methods available (design of experiment, stochastic simulations) for dealing with aleatory uncertainties. The second study [22] was a systematic screening of the engineering design and design analysis literature on the integration of the design analysis activity into the engineering design process. The findings highlighted the need for a more contextual design analysis activity. Thus there should be a large emphasis on design analysis planning, but also on specific design analysis processes. Together with the industry survey this served as a basis for the development of the PDA process model and the specific models [19]. It also gave valuable information regarding QA aspects [21]: 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 risks of utilizing unnecessary time and resources, as well as providing irrelevant results.

Industry survey

The industry survey [15] was performed in 2008-2009. 14 companies participated in the interviews; 10 were manufacturing companies and 4 were engineering consulting companies. The survey’s overall objective was to produce a deeper understanding of the actual interaction between the engineering design process and the computer-based design analysis activities: utilization of design analysis within product development; identification and planning of computer-based design analysis activities; methods and techniques used to carry out the analysis task execution; management and communication of computer-based design analysis results; and finally treatment of uncertainties and errors connected to the design analysis activities.

From the industry survey [15], the support when reviewing the uncertainties connected with design analysis varies from extensive best practices methods at a few companies to the more common approach of formal or informal discussion a the group or department. While the role of QA was identified within the literature study as important for future research [22], the industry survey [15] revealed that only a few of the companies relied on a review-and-check process being performed by more experienced colleagues. Furthermore it was generally felt that the resources (time, money and available competence) on hand for the review of the information available (often just checking the report) are often limited.

It was also found in the industry survey [15] that only two of the interviewed companies have really addressed the verification and validation (V&V) approach of analysis in which validated methods are used for verification. Most companies interviewed in the industry survey [15] state that they address validation of the analysis by utilizing physical tests.
Industrial projects

Elements from the PDA methodology have been utilized by the author and colleagues in industrial practice at the engineering consultancy company Validus Engineering AB. This has allowed both controlling some aspects of the methodology and further developing it. Not all elements of the PDA methodology are utilized in all projects, simply due to the fact that the nature and characteristics of the various projects performed are so diverse and often follow requirements set out by the customers. The elements of traceability, information and knowledge reuse, together with QA, are utilized in all projects carried out. The modalities of progress monitoring follow the minimum requirements set out within PDA, but the level and frequency are adapted to each specific project, which is also the case for communicating the established results as well as the input to future design analysis activities.

About 50 such projects are performed annually. Several projects have been published [20;23-25].

STRUCTURE OF THE METHODOLOGY

Formal definition

The PDA methodology is formally defined in this section, preceded by preliminary definitions.

Methodology: A methodology in general consists of a process model that displays a set of activities and their related methods, techniques and tools [26].

Computer-based design analysis: This is the quantitative simulation of physical phenomena found in engineering practice that are computationally solvable with current state of the art CAE software tools. In relation to engineering design, it is mainly the quantitative analysis of computationally obtainable properties of the product-to-be (the artifact). Among other things it aims at evaluating design proposals, helps explore the design space and reduces the need for physical prototyping. It is an important source of information in decisions taken during the engineering design activity.

Uncertainties and error handling: This is the identification, treatment (mitigation or exploitation), control and documentation of uncertainties and errors.

PDA methodology: the PDA methodology is a specific computer-based design analysis methodology that supports the systematic handling of uncertainties and errors during the computer-based design analysis activity throughout the development of the artifact.

General structure

The methodology presented, see Figure 3, contains the following elements.

1. Methods for handling aleatory uncertainties and epistemic uncertainties
2. Process model with inclusion of both types of uncertainties
3. Specific processes including method development
4. Supporting process (QA activities, progress monitoring, traceability)
5. Documentation of acquired knowledge

Handling aleatory and epistemic uncertainties

The approaches to modeling and propagation of uncertainty within design analysis that are mostly presented in the published literature and used in practice are the following: probability theory, evidence theory (Dempster/Shafer), possibility theory, fuzzy set theory and interval-based theory, see e.g. [27-29].

For the category of aleatory uncertainty probability theory methods have been used to simulate these random, or stochastic, processes by using distributions that are propagated through statistical techniques such as DOE and Monte Carlo simulations. These methods and techniques are used mainly during the execution step of the design analysis. [14]

However, not all variables connected to analysis are of an aleatory nature, and increasing attention is being given to other approaches for handling uncertainty is taking place. In situations where design parameters are described in vague terms or in some linguistic terms that are hard to represent with probability distributions, some of the other approaches might be more applicable from a theoretical point of view. This is particularly relevant when considering the early phases of the
engineering design process, where the level of information is limited and also of a more qualitative (linguistic) nature. Furthermore, when studying a system with a high level of epistemic uncertainties, the possibility of characterizing them with precise probability distributions becomes more challenging from a practical point of view.

However, as discussed for instance in [12] and [28], there is currently not a clear consensus among researchers about the statistical foundation and the practical benefits of introducing the alternative uncertainty theories mentioned above (evidence theory, possibility theory, etc.) within simulations performed today. The main reason stated in [28] is that the Monte Carlo procedures for establishing uncertainty representation for the other uncertainty theories are prohibitively expensive from a practical computational perspective unless combined with variance reduction techniques with the dual purpose of reducing computational cost of a sample run and increasing accuracy using the same number of runs (see [29] for such methods as Latin hypercube and stratified sampling methods).

But, mathematical modeling of epistemic uncertainties is not the only way to deal with them; it may not even be an option for uncertainties at the project, company or environment level. What is important is to be aware of those uncertainties and to plan and execute the design analysis accordingly. An alternative is therefore to have a checklist of categories of recurring uncertainties and an associated guideline for dealing with them. [18]

Within PDA the sources of uncertainties associated with both endogenous and exogenous factors are considered; see [14] (endogenous factors) and [18] (exogenous factors). The aleatory uncertainties are dealt with mostly during the analysis task execution by using established methods and tools mentioned above [14]. The epistemic uncertainties are grouped as several sets of factors according to their levels of influence on the activity; see Figure 4 [18]. The factors elicited are those that have been deemed to have the most influence on the design analysis process. Together with those factors, a guideline presents how to deal with them during design analysis planning and execution within a product development project, and in alternative enterprise configurations. For example, the factors at the enterprise level are best dealt with during the product planning phase.

The overall design analysis process model to which those factors apply is presented next.

A process model integrated with the engineering design activity

The overall design analysis process model established within the PDA methodology is presented in Figure 5. Further elaboration and detailed description of the various sub steps can be found in [19;21]. It consists in the three main activities of analysis task clarification, analysis task execution and analysis task completion of the design analysis activity that are displayed in Figure 5 together with their corresponding steps. The analysis task clarification (step 1) consists of the three steps. In the identification of the task (step 1a), the objective is to ascertain the task relevance and need for design analysis activity, which is followed by the preparation of the task content brief (Step 1b). The aim of the last step, planning and agreement of the task (step 1c), is to reach a mutual understanding and agreement about the task ahead. Within the analysis task execution activity (step 2) the agreed task is further processed in the pre-processing step (step 2a). After solutions have been established in the solution processing (step 2b), the analyses are verified and the result accuracy is assessed (post-processing, step 2c).

Interpreting and evaluating the established results and the model behavior (results interpretation and evaluation, step 3a) complete the design analysis task, and the outputs are integrated back into the project (documentation and communication and integration of the results into the project, steps 3b and 3c). The elicited analysis information and experiences gained are then also communicated to the enterprise for inclusion in the enterprise core knowledge system for allowing continuous improvement (documentation and internalization of acquired knowledge from the analysis task, step 3d).

![Figure 4. Sources of uncertainty connected with factors influencing the design analysis activity.](image_url)
**Analysis task clarification**

The analysis task clarification activity is as important as the analysis execution itself, because it is at that stage that all specifications that will need to be assessed by design analyses are established and agreed upon. Within this activity the following tasks are to be performed:

- The different categories of uncertainties connected with the specification of a certain analysis task should be identified.
- Uncertainties related to interfaces involving data, information transfer between the current activity and other activities in the current project should be identified.
- The proposed techniques to characterize and aggregate (combine) the aleatory uncertainties for propagation in the later design analysis activities should be outlined.
- The way different epistemic uncertainties should be handled shall be described.
- The modalities of task monitoring, level of required traceability, results communication and follow-up of the task activity should be outlined such that all stakeholders have a clear notification on when and how problems during the task execution will be handled.
- Assessment of time, cost, level of modeling expected to resolve and handle the uncertainty in the analyses should be performed.
- State which actions are to be performed by the analyst and which corresponding quality check (QC) activities are to be performed. QCs are based either on self-assessment by the analyst, or on planned checks performed by the assigned resource within the project team with adequate competence in order to assure the quality of the task.

All the above are vital to avoid having the execution activity initiated with unclear understanding of the risks as well as lack of any potential outcome of the current task.

**Analysis task execution**

The identified uncertainties within the task clarification should be characterized and aggregated in the pre-processing of the computational model based on definitions set up in the task content brief. The approach for propagation of uncertainties in the solution processing that can be included in the computational analysis model itself should be defined, for example through statistical approaches such as DOE or other stochastic approaches or through e.g. probabilistic models, or simply by applying common safety factors on the deterministic data; see e.g. [14].

**Analysis task completion: Representation and communication of uncertainty in the established results**

Whenever performing a design analysis the established outcome should be interpreted, documented and presented in a way that facilitates decision making on an overall level throughout the engineering design process. When only communicating the outcome of the performed design analysis to the decision makers the opportunity for collaboration is largely missed. The assessment results of uncertainty propagation during task execution should be further quantified and elaborated so that it can be clearly expressed in the task documentation activities that add value to the performed task. How the established mathematical data should be transferred into descriptive product development information of the product-to-be is part of this activity. Uncertainty quantification should also be used as an input to the subsequent validation activity.

**Analysis task completion: Representation and communication of uncertainty in the analysis models**

The outcome of any incorporated uncertainties in a design analysis needs to be communicated to the project leader and other relevant stakeholders so that informed decisions within the engineering design process can be taken. This includes also the uncertainties related to the analysis model itself. These uncertainties are handled in function of the resources and time given in the brief. This aspect should also be communicated so that the analysis model credibility and confidence can be determined by to the project leader and other relevant stakeholders [11;13].
Specific design analysis process models

The process model presented above gives some general guidance for planning and executing the design analysis task, and for communicating results. However it is not always obvious how an adaption of this general model for specific design analysis tasks should be handled. To that end, a few specific process models have been developed in order to facilitate this transformation. Four of them are presented below (these models can be found in [19]):

1. Explorative analysis activities: In this context, the design analysis activity is performed for exploratory purposes, focusing on gaining better understanding of the product-to-be that will subsequently aim the synthesis design activities.

2. Evaluation and verification analysis activities: In this context the design analysis activity is performed with the purpose of evaluation and verification of a requirement within the product specification list.

3. Physical testing supporting activities: Design analysis activities can be utilized to study and investigate the root cause of unexpected events during a physical test campaign. In addition design analysis is one approach to performing post-test sensitivity and discrepancy studies to elaborate on deviations found when correlating result data between the physical tests and design analysis.

4. Method development activities: Technology or method development activities, in 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 [22]. This can be partially or fully automated. In this context experiences gained and lessons learned are reformulated and developed into appropriate tools and best practice procedures. The possible risks and potential opportunities of uncertainties utilizing the tools and best practices should be thoroughly explicated.

Quality assurance (QA) – supporting the design analysis task

QA aspects in terms of QCs and V&V activities taking physical testing into account.

The QA process consists of self-checks and planned QC activities with the purpose of revealing and capturing any deficiencies connected with both acknowledged and unacknowledged errors in the established computational models, results and approaches used for a certain design analysis activity. Furthermore, a second opinion with regards to treatment of uncertainties should reduce the risk in the choices made. Depending on the extent and the objective of the task, different levels and characteristics of QA activities should be performed. The self-assessment should be performed by the analysts, and the QCs should be performed by an assigned resource. The QC should be considered as an iterative review loop in which the given remarks and comments on the work and responses to them are communicated back and forth between the analyst and the assigned resource for QC until mutual agreement and consensus are established regarding any concerns raised during the review.

Within PDA, verification is interpreted as the assessment of the accuracy of the computational model of the design solution [21]. Furthermore, validation within PDA is addressed as 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. All uncertainties connected with the physical test environment such as the measuring system should be addressed at this stage. Further developments on the QA aspects can be found in [21].

Progress monitoring

Uncertainties connected with the project and enterprise factors (cf. Figure 4) not explicitly treated within the computational analysis model itself need to be addressed and communicated through status and progress reporting on the ongoing work. This should be prepared, communicated and reviewed on a regular basis throughout the design analysis execution as well as the completion activity. It should involve all relevant stakeholders and giving them the possibility to give input as well as draw vital insights from the design analysis activity. The progress and intermediate results are continuously reviewed and evaluated during project review meetings. Furthermore, all known uncertainties, originally listed as well as newly encountered, connected with the task should be discussed during the review so that an updated risk assessment of the design analysis activity can be made. In this way deviations are caught early and expensive, time consuming iterations are avoided. This also allows all stakeholders to make necessary assessments and mitigations or corrective actions on the ongoing engineering design activity as well as on any other project activities that are connected to or dependent on the current design analysis activity.

Traceability in utilized information, technologies and established results

All models, data and information established during the execution of the activity should be gathered in some form of tracking system that could either be in the form of engineering data management (EDM) or based on a file system approach. The stored data and information would serve as the backbone for investigations in and retrieval of data and information at a later stage within an ongoing design analysis activity, or even when it has been completed, thus reducing the risk of the project and enterprise ending up in situations where previous data cannot be re-established. Furthermore, it allows for efficient scrutinizing and mitigations of intermediate results data in the case changes in the development project affecting the design analysis activities occur.

Various forms of meta-data, such as key input data and results, can be extracted and stored in the system to aid in the
tracking and identification of relevant data. Also the responsible engineer for each input in the tracking system should be clearly identified.

The tracking system should also serve as a vital link between the established analysis results, the various models used to establish these results, as well as the history of the various model generations. Additionally, intermediate and final documentation should also be linked to the tracking system so that one can track back the content they present (results, analyses models, used software and in-house scripts).

Minutes of project meetings taking place during the execution of the design analyses activity are also important for the traceability of agreed actions and changes to the originally defined scope. These changes of course must also be included in an updated version of the task content brief (or task specification) that should always describe the actual agreed description of an ongoing task.

**Documentation of acquired knowledge**

*Input to future design analysis activities*

Another context is method development projects (cf. third specific process model above) in which experiences gained and lessons learned should be reformulated and developed into appropriate tools and best practice procedures. Without proper attention to the handling of uncertainties and review of potentially incorporated errors in the design analyses activities, the established methodologies and guidelines would provide less confidence when basing future activities on them. Even worse, they might be based on the wrong foundation and could thus potentially hamper future success for the enterprise.

The method development approach adopted within PDA is that the analysis experts within an organization or at software developer/vendor sites provide the design engineers or less-experienced analysts with a template or guidelines of a specific analysis situation in which the uncertainties are addressed by a set of appropriate simulation variable choices and boundaries that have gone through the verification and validation procedure. The template or guide should preferably be presented in the form of a number of steps (guidelines) in which the user should make decisions regarding one subject at a time. The benefits of the standardization of certain simulations within large organizations are obvious. A further benefit with regards to QA aspects and training of new employees is that everyone within an organization is performing the simulations in a similar and controlled manner. Finally, such an approach facilitates the possibility for a more straightforward incorporation of simulation data and information gathering for later reuse.

**Information and knowledge re-use for an improved confidence**

A NAFEMS survey on design analysis practices [30] found that education and training of key practitioners on the appropriate level as well as exploitation and dissemination of the technology (including particular issues concerning QA and software V&V) are critical barriers to overcome to facilitate broader use of the design analyses activities. This was also confirmed by the literature study [22] in which 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. The data, information and knowledge generated throughout design analysis activities should be stored at the enterprise level such that these elements and their related uncertainties can be transferred to the organizations performing the concurrent development activities. If some lack of understanding or completeness is encountered in this process, training programs should be initiated.

**CASE STUDY**

In the following case study, several elements of the PDA methodology are emphasized: handling of epistemic uncertainties, acknowledged and unacknowledged errors; application of QA methods such as self-checks, QC or V&V; use of the specific process models (explorative design analysis, physical testing supporting activity, method development).

This case study presents the development of a device transportation system (DTS) [23] for a semiconductor device, hereafter referred to as the “shipped device”; see left picture in Figure 6. 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 right picture in Figure 6 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 at any point on the shipped device and at any time should not exceed a specified level. This includes both horizontal and vertical shock loads as well as vibration. The design should also be able to handle landing and takeoff with aircraft without the shipped device exceeding a certain angle of inclination. 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. Specifications for the final physical acceptance tests that were to be performed were also added to the product specification.

During the task clarification of the initial conceptual design analysis activity of the system (represented in the middle picture in Figure 6), the appropriate combination of design analysis software (MBS and FEA in this particular case), and resources were discussed. 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 activity ahead based on the present state of knowledge both within the project and the also within the enterprise. In the current case, approaches based on MBS and FEA were compared. Both approaches currently provide straightforward interface to CAD model geometry that reduces the risk of errors being transferred in the interface from modeling to analyses.
The selected MBS approach has the following advantages over FEA: it provides fast analyses, which is beneficial with regards to uncertainty regarding time constraints, and good representations of damper and spring elements, thus reducing the modeling uncertainties. On the other hand one of the drawbacks is that it can only provide linear model flexibility of the studied structure. Therefore some safety factors on the loading were applied in order to account for this known limitation. Furthermore, the choice of a representative selection of load cases, out of all defined load cases in the specification, required fully developing the design needs to be decided upon such that at this early design stage any decisions taken based on the results from the limited state of knowledge could be judged adequately. The initial results were communicated to both the customer and to the suppliers through review meetings. During the review the supplier provided updated information regarding the shock absorbers for which the damping coefficients shifted from the linear to a non-linear curve. Thus the selected modeling approach that had been utilized so far had to be changed to the FEA approach due to the limitations in MBS.

The basic layout of the frame of the DTS was established through a subsequent design analysis activity in close collaboration with the engineering design department. Figure 7 presents a number of the frame layouts in the iterative process of finding a suitable overall layout with the initial model on the left and final model on the right. For each iteration, self-checks and QCs were performed within both departments. Furthermore, all established models were stored within the tracking system established for the project so that all intermediate models, results and assumptions going into them could be tracked and possibly re-used at a later stage of the current project if late changes to the specifications required a reconsideration of the design or within a subsequent project with different specifications.

Preliminary layouts for the auxiliary functions of handling the DTS during transport were also included in order to incorporate them into the complete system.

In Figure 8 the results from the vertical collision test 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 are 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 7) it can be seen that the fourth layout has the overall lowest stress levels during collision.
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 detail design phase.

In a later stage of the development, a design analysis activity of exploratory nature was executed to determine the most robust location of the vibration insulation components. The uncertainty in spatial placement and vibration insulation characteristics was studied. In Figure 9 (top) the acceleration results from two of the placements studied (horizontal and vertical) are displayed for two locations (center of gravity, COG, and top) on the shipped device. Accelerations (Acc) are presented as a function of time vs. acceptable (requirement) acceleration. The plots clearly show that the horizontal location results in a more robust response than the vertical placement. The final placement and mounting of the vibration component based on these findings is displayed in Figure 9.

The general objective of the design analyses within the detail design phase was to facilitate the selection of a final design that would withstand the loads that the DTS is exposed to during all phases of its life cycle. In the case study, the dynamic nature of the shipment of the shipped device was identified as the main concern that might decrease durability of the DTS.

Thus, in addition to the linear static and dynamic design analyses induced by equilibrium and collisions, lifetime evaluation was being performed, in which the effects of the vibration load histories were considered.

Since no load history data from the different shipment functions were available in advance, these data were extracted from standards [31;32]. The upper left picture in Figure 10 displays a couple of applicable standards where the Power Spectrum Density (PSD) versus frequency is plotted.

The total fatigue life estimation, i.e. the possible number of shipments, was calculated by following a procedure developed from earlier DTS projects describing a number of steps to be performed in a guideline format for establishing the life time estimation based on the Palmgren-Miner rule. The development of the procedure was the result of the aforementioned specific process of method development.
In this procedure, all relative fatigue damages from the time durations of all shipping activities are combined into an overall fatigue damage that is compared to the material stress-life curve (S-N curve), like the utilized frame stainless steel SIS 2333-02 (comparable to AISI 304) material displayed in Figure 10 (bottom right).

These in-depth lifetime evaluations were performed on a number of locations on the DTS. One of these locations is presented in Figure 11 where the left picture represents the model utilized in the embodiment design phase. The overall coarser FE discretization is well suited for the embodiment design phase, in which the overall stiffness and stress levels are more important than the specific stress at a specific point that must be verified through some convergence study. Two models with increasing levels of detailing (increased number of shell elements, see middle picture in Figure 11, and detailed solid elements, see right picture in Figure 11) were established in the convergence study performed with the purpose of studying the discretization uncertainty in the mesh distribution and simplification of the FEA model. As can be seen in the refined shell element model and solid element model, the stress levels and stress pattern are quite similar, and it was concluded that the refined shell model was sufficient to predict the stresses in relation to the fatigue evaluation; see Figure 10. Nodal stresses are shown for the solid model for clarity (not showing element edges) since the difference to element stresses is insignificant.

Figure 11. Comparison of results from the different preliminary layouts of the DTS (courtesy Validus Engineering).

Figure 10. Fatigue life evaluation using Random Vibration in ANSYS (courtesy Validus Engineering).
After all components and parts were designed and manufactured, and physical testing was to be performed to evaluate the product’s compliance with the design specifications. These tests were performed on the system level where the overall function and some of the main functions were studied along with specific lifetime evaluations extracted from strain gauges and accelerations at the locations on the DTS, as well as the shipped device established in virtual prototype testing analyses performed prior to initiating the physical test. A number of tests were performed for each situation, and the test curve in Figure 12 displays one of the situations. Accelerations (Acc) are presented as a function of time vs. acceptable (requirement) acceleration. The test curve is the average results from the tests, and the simulation curve is the average results based on the results from analyses with actual initial measured data from the physical test. In Figure 12 the test setup and the correlation of the test results with virtual prototype simulation results are presented for the side collision load cases.

The validation of the simulation model was performed by comparing the results obtained from the physical testing. When evaluating the level of correlation of the results, uncertainties and errors connected with the physical testing environment should also be considered. For instance Figure 12 highlights that a DC disturbance of 50Hz is present in the test results (see the alternation in the signal) due to problems with the top sensor in the longitudinal direction. Another aspect of utilizing test data is filtering of the extracted data. A too-high threshold in filtering frequency might exclude important peak data in the results. Being confident that the analysis model was capable of correctly predicting the results from the load cases that formed the basis of the product specifications, it was possible to extensively evaluate the DTS by using design analysis results.

The main lessons learned regarding the design analysis activities were gathered at a project closure meeting. Queries and answers as well as minutes taken at various meetings held during the project concerning design analyses activities were also studied. At a separate methodology meeting, some established lessons learned were selected for further development and investigation with the purpose of incorporating them in the company design analysis activity guidelines.

CONCLUSION
Taking into account uncertainties, with dedicated techniques throughout the design analysis activities, is important in order to provide other stakeholders with a certain level of confidence in the decisions based on the design analysis task outcome. The PDA methodology presented provides a systematic and well-founded guide to handle uncertainties and errors related to design analysis activities. This allows for an increase in the confidence in the design analysis process and results used in a development project.

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Paper VIII

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

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

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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 influenced 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; Ehrlenenspiel 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. Ehrlenespiel (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 process 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.
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](image-url)  
**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).](image-url)
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.

![Diagram of Design Analysis Basics, Product Development Project, and Developing Enterprise Environment]

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.
The GDA process model and factors influencing it.

Factors influencing the GDA process model

A. Design analysis basics
1. Material
2. Loads
3. Boundary and initial conditions
4. Modelling
5. Discretisation
6. Programming

B. Product development project
1. Specifications
2. Purpose
3. Level of concretisation
4. Time
5. Costs
6. Process monitoring

C. Developing enterprise
1. Hardware
2. Software
3. Quality assurance framework
4. Organisation
5. Employee competence
6. Procedures & enterprise-stored knowledge

D. Environment
1. Legal regulations
2. Environmental
3. Regulations
4. Hardware suppliers
5. Software suppliers
6. Customer standards
7. Industry standards
8. Certifying standards

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.
Rigid car plates move as one rigid body

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.
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

![Optimization History]

Mass

![Optimization History]

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.
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 multi criteria 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 emanate 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 multi criteria 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 multi criteria decision-aid: “The first fact which should be noted when dealing with this type (multi criteria, 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, multi criteria 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
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).](image)

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.
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.

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.
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.
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:
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.

The pallet, see left picture in Figure 18, supporting the DTS during the testing was designed (4) and analysed as a pre-test analysis in order to assess 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

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

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).](image)

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.
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 valve 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 in-depth 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 verification of the developed template (13). During the same phase an extra verification 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. 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

Table of the settings

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Figure 21. Some outputs from the template.
Figure 22. Workflow of the method development of a template for the design analysis of exhaust valve seatings.
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.

References


