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

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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 and 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 and Wood 2001], [Ullman 2010], [Haik and Shanin 2010], [Ulrich and Eppinger 2012], [Dieter and Schmidt 2013], computer-based design analysis is not emphasised in the process models. In the few cases where it is mentioned, e.g. Ehrlenspiel [2003], the German versions of Pahl and Beitz [2005], and the VDI Guideline 2221 [1993], it is only considered as a part of the verification of the product properties and described in a non-operational manner.

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

In order to accommodate the explorative nature of the survey, a semi-structured interview method was utilized; a detailed account of the actual approach is presented below. The structuring of the questions is based on design analysis activities within the engineering design process and thus the interviewees were managers responsible for the computer-based design analysis activities and/or engineering design/product development managers. Furthermore, the survey focuses mainly on the utilization of finite element analysis (FEA) within computational structural mechanics (CSM) simulation. *Note:* Since the survey was carried out between 2007 and 2008 and the analysis of the obtained information from the survey was finalized in 2009, the intention was only to publish the survey results in separate publications. In all, several of the survey results have partly been utilized in three publications [Petersson et al. 2012], [Eriksson and Motte 2013a,b]. 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 and 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 and 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. [2009] have empirically investigated the need for communication between engineering designers and analysts (four engineering designers and four analysts of a German automotive manufacturer), with the aim of improving the effectiveness of collaboration between embodiment

design and simulation. It is also not possible to just ‘hand-over’ one’s design to the analyst and consider computer-based design analysis as a black box.
Another survey in Germany has been performed by Kreimeyer and colleagues [Kreimeyer et al. 2005], [Kreimeyer et al. 2006], [Herfeld 2007, pp. 75-91] in the German automotive industry (both OEMs and subcontractors) to which 33 engineering designers and 16 analysts replied. The goal of the survey was also to get better insight regarding the quality of efficient collaboration between engineering design and simulation departments. Some of their main findings were that engineering designers saw the analysts merely as “service providers” and failed to consider their integrated role in the overall engineering design process; communication and collaboration during analysis planning to set common goals and during analysis result interpretation are seen as key elements.
Finally, a survey by NAFEMS published while this publication was finalized, the NAFEMS Simulation Capability Survey 2013 (1115 respondents), points out that nowadays nearly 30% of the analyses are done during the conceptual design phase [Newton 2013], confirming that design analysis now perspires the entire engineering design process.
The reported surveys have established that there is need in industry for a closer collaboration and integration between engineering design and computer-based design analysis activities. In the presented survey, this need for collaboration and integration is studied at a detailed level: 1) it is investigated for the different types of utilisation of computer-based design analysis in product development; 2) it is also investigated for the different phases of the design analysis activity. Following the framework from King et al [2003], the emphasis is on the process, not on the aspects such as software, hardware and the like.

3. Approach[1]

3.1 General approach

The lack of a commonly accepted terminology creates major problems whenever attempts are made to extract information from the mechanical engineering design process; this is especially valid when design processes in industry are surveyed. To decrease to at least some extent the impact of these problems, a survey technique based on combination of a questionnaire and interview was chosen that already have been proven successful in [Bjärnemo 1991] and [Bramklev et al. 2001]. In this combination, the questionnaire was merely intended to prepare for the interview and was sent to the interviewed people in advance. The following procedure was followed: Potentially interesting/-ed companies were contacted; a letter describing the overall purpose and goals of the survey accompanied the questionnaire; the interviewers then visited the company where the respondents answered the questions sent in advance. All the interviews were recorded.
The selection of the relevant companies is described in the next section. The interviewed persons in each company were generally responsible for performed computer-based design analyses activities at each company and in some of the companies also responsible for the entire product development departments. In some of the companies analysts participated in the interviews.
After each interview, the tapes were listened to and the interviewee’s oral answers to the questionnaire were written down. The document was then sent to the interviewee who had the possibility to complete or adjust it. The corrected document was reviewed against what had been said in the interview to check for any discrepancy. No such discrepancy was found for this survey. Once all the interviews were completed, one person summarized the answers and the points that were deemed relevant to the purpose of the survey were extracted. The other interviewers then shared their view on the summary and synthesis in relation to how they had perceived the interview; following this discussion, an agreement could be reached.

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

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

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

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

Table 1. Company characteristics

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

3.3 Structure of the interview

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

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

4. Results of the survey

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

4.1 Utilisation of design analysis within product development

Use in the different phases of product development: Nine companies are preforming design analysis throughout the complete engineering design process; three are using it only for the later phases of the engineering design process and two of the EC companies mentioned that is primarily driven by customer requests.
Nature of the activity: All companies use design analysis to evaluate product proposals. Three TS and CC companies and all EC companies say that they do product simulation (of the complete system). Five companies out of which three are EC use design analysis methods or tools, such as topology optimization, in the synthesis activities of the concept and product definition. Five of the companies say that the design analysis performed in the later product development phases include a verification step (see definition Section 4.3). Validation is usually carried out with physical prototypes, but four of the TS and CC companies and all EC companies say that they rely on analysis as validation when other means of validation are not possible. Finally, two companies assert that they do phenomenon studies reported from complaints and failure situations.
Occurrence of supplementary analysis: The analyses performed often lead to further supplementary analyses based on advice from analysis department, represented by the analyst, in collaboration with the designers and project members. This is generally very common within the interviewed companies, but the purpose varies greatly. Some of the mentioned purposes are:

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

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

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

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

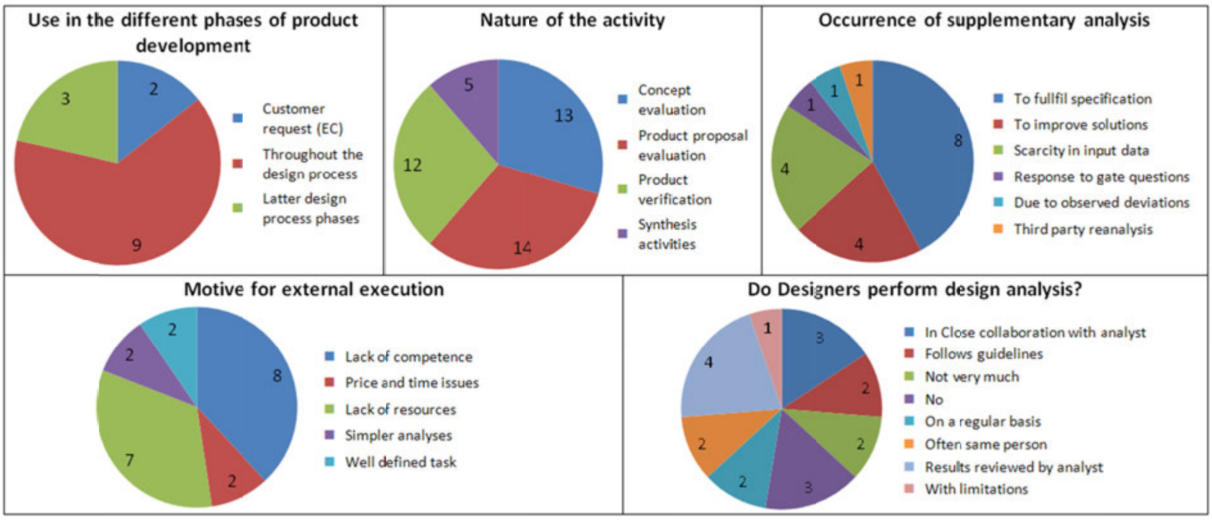

Figure 1. Utilisation of design analysis within product development

4.2 Identification and planning of computer-based design analysis activities

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

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

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

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

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

- Documented best practices are used. Such a document gives guidance, based on gained knowledge from previous design analysis activities, with information on how an analysis is to be performed. Eight companies use this approach.
- The knowledge among the experienced employees and departments involved is utilized as the foundation for establishing the analysis approach. Six companies use this approach.

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

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

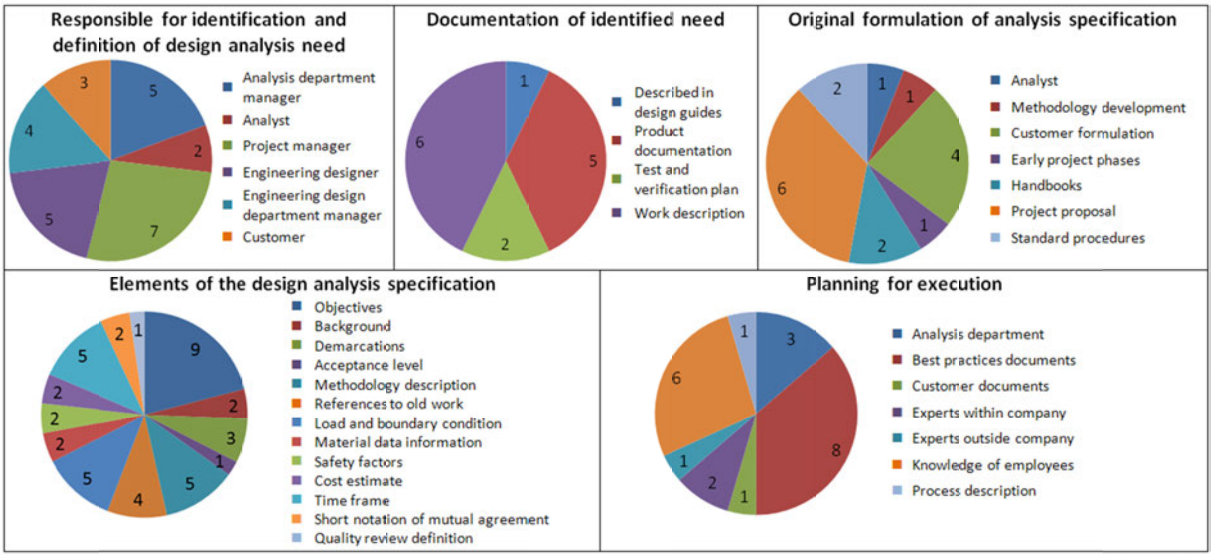

Figure 2. Identification and planning of computer-based design analysis activities

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

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

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

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

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

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

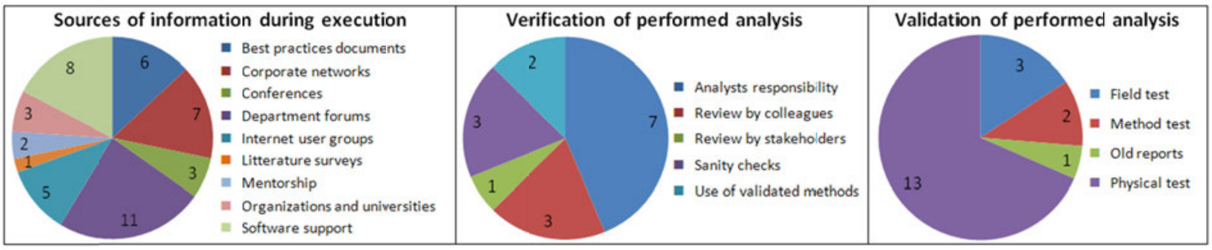

Figure 3. Methods and techniques used to carry out the analysis task execution activities

4.4 Management and communication of computer-based design analysis results

The management and communication of the produced results and information as well as the established analysis files are an important part of the feedback, documentation and future traceability of the performed activities. EC companies say that both the form of and the content of design analysis outcome feedback generally depends on the customer requirements. The established documentation is presented and discussed at dedicated meetings or gate review meetings within five companies.
At seven companies, effects of design modifications are investigated by some variants of design sensitivity study or other assessment. Furthermore, two companies mention that the documentation should also contain interpretation of the results and engineering suggestions based on the results.
Documentation is stored in data management systems for eight of the TS and CC companies and one of the EC companies. Only one company stores the complete FEA-files in a product data management (PDM) system. One TS company and two EC companies mention that they store intermediate, unpublished, analysis findings such as execution information and results along with gained experience. There exists a model archive at one of the TS companies were each meshed component is saved for reutilization in other analyses. The other companies use a file system also for the reporting.
One company mentioned that it once had a forum in its analysis department where lessons learned should be stored. However, the utilization was very low and the forum was closed after two years. Also one company mentioned that when performing new analyses that is to be based on old data, they experienced that generating the model again is often quicker than try using an old model.

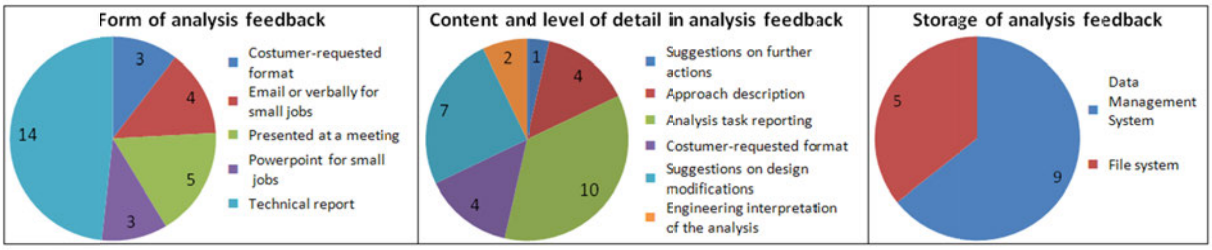

Figure 4. Management and communication of computer-based design analysis results

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

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

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

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

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

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

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

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

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

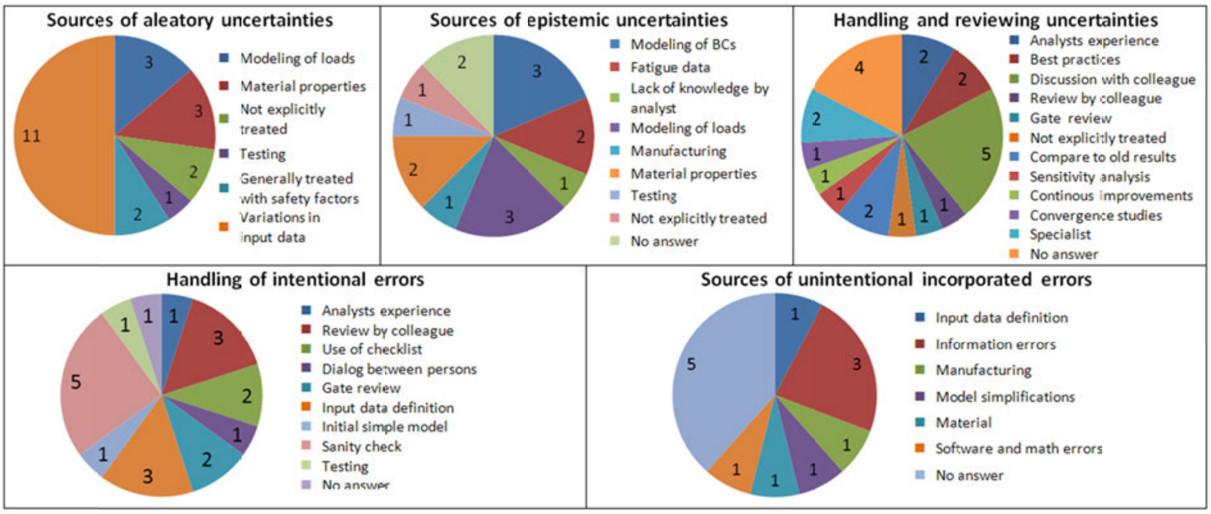

Figure 5. Treatment of uncertainties and errors connected to the design analysis activities

5. Discussion

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

5.1 Utilisation of design analysis within product development

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

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

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

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

5.2 Identification and planning of computer-based design analysis activities

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

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

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

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

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

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

5.4 Management and communication of computer-based design analysis results

Communication of the results: Although all companies state that they present their analysis activities in technical reports, only two of them mention that engineering assessment of the design analysis results are performed. This is somewhat interesting in the light that seven companies mention that suggestion to design modification based on the results are often included in the reporting. Without

engineering interpretation of the assumptions and approaches used in order to establish the results at hand, the value of these suggestions might lack adequate foundation.
The documentation should also give information regarding the interpretation of each load on a system level but also broken down to each physical discipline under study and couplings between these in a multiphysics environment. This is an important asset when the design analysis activity is clarified and planned.
Storage and re-use: The companies with most employees involved in analysis have some information exchange in corporate networks between development departments at the different facilities. Interestingly only one CC and one EC company use some form of mentorship to transfer corporate knowledge as well as experience to the newly employed colleagues. Out of the five companies that use Internet user groups as a basis for information search, three of them were EC companies and two were CC companies. Two of the EC companies state that all analyses are saved for the future. At one TS company, the files are stored for ten years; however, the archive is not searchable. Therefore, it is hard for a third party to exploit it. This aspect should be addressed when planning for system to handle the ever-increasing amount of data connected with design analysis activity. Note, however, that on a longer perspective both hardware and software might have evolved so much that opening an old analysis might introduce uncertainties that might be at least as time consuming to assess as establishing a new model. Utilization of already established analysis information when defining and/or performing a feasibility study of a new project is not much discussed within the companies.

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

Uncertainties: The lack of control over input data give induces a need for review management of this information. In addition, the uncertainties linked to the product development project have to be addressed, in other words, it is necessary to be ensured that the adequate analysis and evaluations are performed in an appropriate manner. Furthermore, more uncertainties are introduced with parallel evaluation in a multiphysics project and when other disciplines of a product development process (industrial design, manufacturing, marketing sales) are involved. The companies should address this aspect more systematically.
Assessment support: Three of the companies describe that they rely on sanity checks to be performed by the analysts as a part of self-assessment of the results. This is of course a well-founded approach for experienced analysts for justification of their own produced results. However, for a less experienced analyst this can be a problematic task, that in a worst scenario, could lead to incorrect decision. Furthermore, it will most certainly mean that interesting second level information will be lost by the company if lessons learned are not stored within the company.
One company puts forward that sensitivity analyses should always be performed when evaluating the results, however this is not necessarily sufficient: these additional analyses bring understanding to the sensitivity of the utilized model but it is also necessary to have a holistic view on how the model was established in order to ensure a suitable appreciation of the potential uncertainties and errors. It is also concluded that the resources (time and money) available for the review of the analysis results could be increased since this was identified as a bottleneck in many companies. The back-to-back comparison of analysis results is of course a good source of information when performing evaluations of products already known to the company. Nevertheless, it will have less importance when studying new, not previously executed analysis, either by the engineer, department or elsewhere within the company.

6. Conclusion

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

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