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Integrating Engineering Design and Design Analysis Activities at an Operational Level

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Abstract

Computer-based design analysis is nowadays of utmost importance in most engineering design projects. However, this brings some challenges, among them that of the collaboration between engineering designers and design analysts. Since they work with, and are responsible for, different areas, they do not necessarily have full insight into each other's way of working. The issue of integration between the design analysis process and the engineering design process is thus of major significance for providing an increase in efficiency and effectiveness in engineering design and development of products. In this work, an approach is proposed aiming at providing this increase in efficiency and effectiveness. Based on the analysis of the information workflow between the engineering design process and the design analysis process, a mapping of the necessary interactions between engineering designers and design analysts can be made. The presented approach facilitates this mapping. An application of this approach to an industrial project is also presented.

1 Introduction

The significance of design analysis within engineering design and product development is well established. In the NAFEMS Simulation Capability Survey 2013 [Newt-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.

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.

The use of design analysis, in the given context, 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 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. While the problems confronting the engineering designers are predominantly of an open-ended nature (mainly synthesis), the analysts are mainly focusing on convergent problems of an analytical nature. 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. A similar increase in efficiency and effectiveness of the design analysis process is expected, together with an increased understanding of the nature of engineering design by the analyst.

A successful integration of the activities of engineering design and design analysis requires integration of the process, the organization, and the information system [MoBB-2007]. In this work, we present an approach to facilitate the integration of engineering design and design analysis activities regarding the process. Integration can be considered at the strategic level, at the tactical level or operational level. At the strategic level, integration activities regards the definition or refinement of the company's standard product development process model. At the tactical level, they regard the adaptation of the standard process model to new development projects. The operational level deals with integration at the task level. Our work is predominantly concerned with interactions between the engineering designers and the design analysts at the operational level, and partly at the tactical level, although at a detailed level. For integration at the strategic and tactical level, see the comprehensive work of [KrLi-2011].

The proposed approach is presented in Section 2 and further developed in Sections 3 to 6. An application of the approach on an industrial case is given in Section 7. Finally, the approach is discussed in Section 8.

2 Proposed Approach

In this section, the complete approach is described. The details are presented in the following sections.

To increase integration between engineering design and design analysis, the following approach is developed in this publication. We posit the following (which is also developed further in the following sections):

- Although there exist generic engineering design process models in the literature (e.g. [PBFG-2007]) companies utilize specific process models that can be both far from these models and very different from each other's. Moreover, the companies often adapt these models to specific projects, thus making these differences even more obvious. Therefore, our approach only includes a minimalistic model of the engineering design process. More on that in Section 4.
- Contrary to the existence of generic engineering design process models utilized in industrial practice, there are strong indications for the existence of a generic design analysis process model used by many companies and analysis departments for analysis tasks of different natures with relatively few changes (this applies within the frame mentioned above in which design analysis usually is performed by the analyst, employed by either the company or an engineering consulting company). This generic process model, here denoted the generic design analysis (GDA) process model, is motivated and briefly described in Section 5.
- Given a specific engineering design process model and the GDA process model, the information workflow analysis allowing for an integration at an operational level occurs in the following way:
    - The structure of the GDA makes visible recurring activities, which require collaboration between engineering designers and analysts. For each new design analysis task, these recurring activities should be systematically reviewed and interactions identified and planned
    - Also a subsequent analysis of the information workflow between the engineering design and design analysis activities specific to the project will help identify further interaction points between both processes.

The information workflow analysis is described in Section 6.

There are conditions for a successful application of such an approach. One of them is that the engineering designers and analysts who need to collaborate must have a mutual understanding on each other's activities. This approach cannot work if both parts consider the other's activities as a black box. This is elaborated upon in some detail in Section 3.

Note that an alternative approach to the one presented here would have been to utilize one of the generic engineering design process models from the literature and describe for each phase and activity the relevant design analysis tasks. This strategy has been applied among others in [BjBA-1993] where design analysis tasks that were the most appropriate for the different phases and activities of Pahl and Beitz' [PaBe-1984] engineering design process model were described. Although relevant, this approach is more difficult to adapt to each company whose engineering design process model and related product development process model are specific to the company and its products.

3 Conditions of Application of the Proposed Approach

3.1 A Necessary Condition: Mutual Understanding

Whatever engineering design process model and design analysis process model are used, it is of utmost importance for both parts (engineering designer and analyst) to have a general understanding of each other's work. This should be achieved at best during engineering education but can be also done during professional training as well as through experience. It is necessary for both parts to have good general knowledge about the engineering activities both are performing as part of their profession. The engineering designer needs to understand what an analyst can achieve given a time and resource frame, and the analyst should be aware of what he/she needs to know from the engineering designer to make an efficient and adequate analysis. In addition, an engineering designer, as the ordering party, needs to be able to participate in the establishment of relevant objectives, and adequate acceptance criteria for the evaluation of the design analysis. For example, does the analysis aim at understanding a physical phenomenon, at giving recommendations for the choice of a concept, or recommendations for improvements?

The workflow analysis below helps identifying and developing interaction points between both parts but will not be very effective if there is limited knowledge about each other's activities.

3.2 Facilitating the Application of the Approach: Other Integration Aspects

Other aspects of integration that help are, as mentioned in the introduction:

- An overall integrated product development process model (of which this work is a part)
- Organizational integration
- Information system (IS) integration

These aspects are important. For example, in the company's master product development model, analysis activities might be already embedded. They can also be planned at the product planning level [ErMo-2013a]. Organizationally, engineering and analysis departments could be more integrated. Some companies are considering this; in [PeMB-2015], one interviewed company reported having implemented such an organizational change, now completed. Finally, an effective IS allows for exchange of data, engineering and computational models and results in a very smooth way. This is one of the goals of Model Based Design. By introducing Model Based Design in CAD software, the CAD and CAE tools share the same data model. For example, in 3D Experience by Dassault Systèmes [Dass-2016], CAE data is connected to the CAD data throughout the product life cycle, allowing traceability of the CAE data. Much more can be said about these elements, but this publication here is confined to the interactions occurring at the operational level (the knowledge of which can help companies further develop other aspects of integration).

4 Perspective on Engineering Design Process Models

It is important to posit that the engineering design process is one of the constitutive, parallel, processes to be undertaken during a product development process – see [OlCB-1985]. Furthermore, it is also important to notice that the engineering design processes model is specific to each manufacturing company and sometimes even to a specific engineering design project.

Some examples of factors affecting the establishment of a specific engineering design process model are the diversity of the products to be designed and the nature of the engineering design project (are we focusing on a one-off product or is the product expected to be developed further in the future?). In addition, the educational background of the engineering designers, their experience and cost and time constraints are also crucial factors in establishment of the process model. As a result, the process models used in industry present a very large variation. Using one of the generic engineering design process models provided in literature as a basis for the described approach would require systematic adaptation. Such an adaptation would be not only difficult but also time and cost consuming. There is also some support in the literature for using alternatives to generic engineering design process models. An interesting and flexible approach to the establishment of an engineering design process model is the utilization of process elements. In the book *Integrated Design Engineering* [Vajn-2014] this approach is introduced based on a doctoral thesis work by Freisleben [Frei-2001]. In her thesis, 51 process elements forming elementary design activities have been identified and formulated. These are all needed to establish a process model for the design of a new product, while fewer elements are needed in adaptation or variant design.

In the design and development of products in an industrial setting, a number of problems of both an analytical and synthesis-oriented nature need to be addressed. The majority of these problems are of a synthesis-oriented, open-ended, nature. One example of such a problem is to establish the facts needed in the evaluation and subsequent decision of a number of design solution candidates. A number of possible approaches are open to the engineering designer such as testing, design analysis and comparisons with existing designs. In other words, the engineering designer is facing a problem of an open-ended nature, for which the solution is dependent on the access to expert knowledge and of project constraints such as costs, time etc. One of the experts to consult is the analyst, who needs to interact with the engineering designer at an early stage of the decision process, in order to provide all the data needed to facilitate the decision. If design analysis is chosen, additional interactions are needed between the engineering designer and the analyst before the actual analysis projects is fully planned and ready to be executed. This is where the information workflow analysis (Section 6) is of particular importance.

5 The Generic Design Analysis (GDA) Process Model

If the engineering design process presents large variation in its sequence and activities, design analysis, by its nature, presents for most tasks the same fundamental sequence and activities. These recurring design analysis activities can be grouped in three phases. First, design analysis in an industrial setup is most often performed by analysts (within or outside the company): they might have only a partial knowledge and understanding of the design problem; time, cost and resource allocation are also constraints to take into account. This requires an understanding and agreement about the design. These activities constitute the *analysis task clarification* phase. Next, there are specific activities to perform the *analysis task execution* itself: development of a representative engineering model as well as the actual computational model for solution (pre-processing activities), solution processing, and post-processing (e.g. check for accuracy and convergence). Finally, the analysis task results must be interpreted, documented and communicated into the overall engineering design/development project that needs to integrate it back to the design project. These final activities constitute the *analysis task completion* phase.

These elements are recurring in virtually all design analysis literature as well as industry, see [MEPB-2014] for a review. This is due, as explained above, to the very nature of design analysis and its relatively well-defined scope. This allows for the development of generic design analysis process models. One of these models, developed in a doctoral thesis by Eriksson [Erik-2015], presents in a detailed way the core activities of design analysis. This detailed level allows for an easier integration at the operational level between synthesis and analysis activities. This model is represented in Figure 1, with, for each activity (1a to 3c), the corresponding core sets of sub activities. The core sub activities are not always enough to cover all aspects in every foreseeable design analysis task and specific sub activities might be needed; vertically denoted as "…-n." in Figure 1.

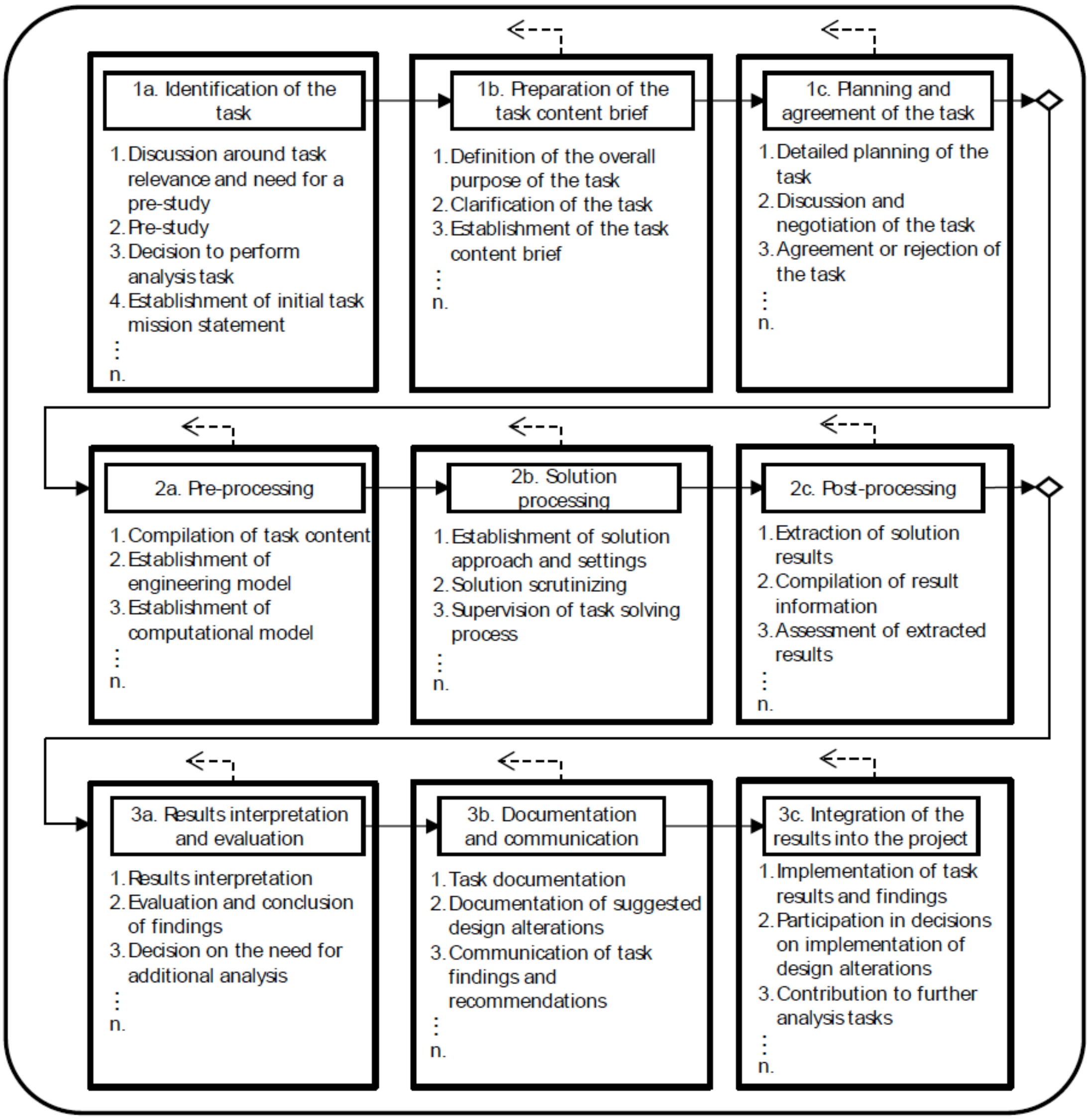

Figure 1: The GDA process model with defined phases and core activities [Erik-2015]

6 Integration at an Operational Level – Information Workflow Analysis

6.1 Recurring Interaction Points

For every design analysis task there are interactions between both disciplines that will occur whatever the task. These are taken into account in the following workflow analysis and they will ease a successful interaction.

6.1.1 Analysis Task Identification Phase

During this phase, both parts will interact quite often:

- To discuss the task relevance and agree on a pre-study —if needed,
- During the pre-study (when needed) and to decide whether or not the complete analysis is relevant,
- To discuss the analysis specifications (the task content brief),
- To plan the execution of the task,
- If necessary to negotiate the task,
- To reach a common agreement on the task.

6.1.2 Analysis Task Execution Phase

While the analyst is in charge of the execution of this task, several interactions are necessary (see also [Erik-2015]):

- Interactions for 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. Any new or updated information, emerging outside the design analysis activity as well as from intermediate result findings from the design analysis activity, applicable to an on-going design analysis task should be communicated among stakeholders involved, such as the analysts, engineering designer and project manager. This will provide the stakeholders with 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 task. Figure 2 illustrates the information flow of progress monitoring activities.
- Interaction for review and control activities: The control and review activities within the execution and completion phases of the GDA process consist of quality checks 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 outcome of the quality checks are important feedback to the project team, such as the engineering designer and project manager, 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 3 illustrates the information flow of the control and review activities.
- Interaction due to traceability: All models, data and information established during the analysis activities generally are (or should be) gathered in some form of tracking system that 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. This tracking system 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. It also allows efficient interactions by tracking back minutes of projects and review meetings during the execution and completion of the design analysis task. Finally, data from previous projects can be used for planning new design analysis tasks by tracking back the previous interactions between engineering designers and analysts. The data can therefore be used in the information workflow analysis.

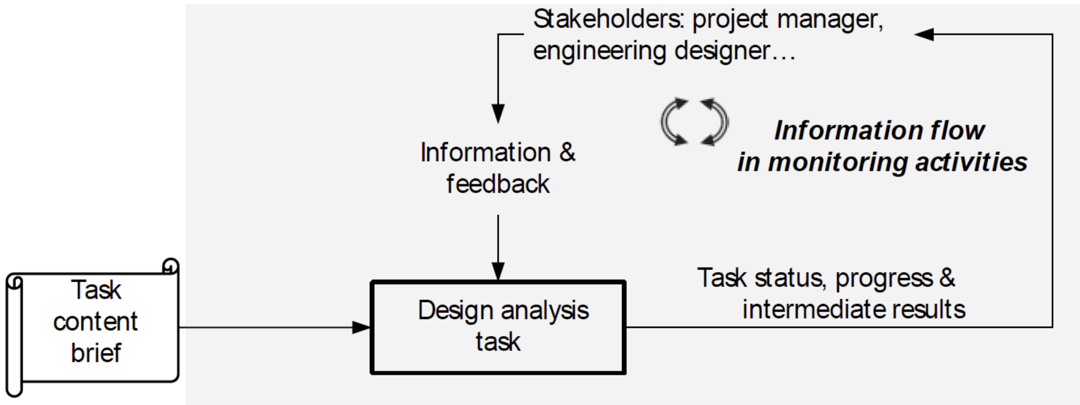

Figure 2: Information flow within progress monitoring activities, from [Erik-2014]

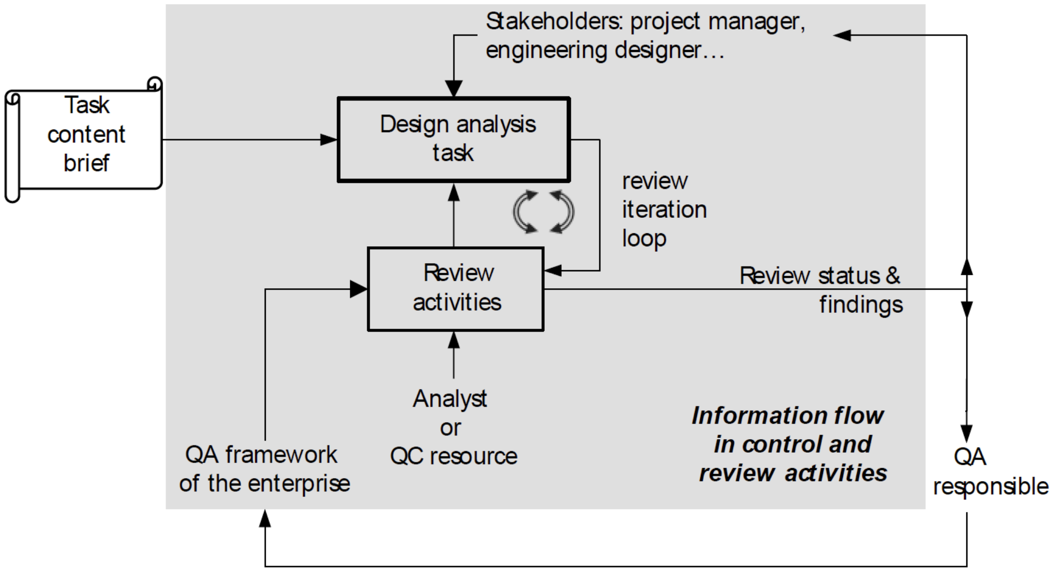

Figure 3: Information flow of the control and review activities, from [ErMo-2013b]

6.1.3 Analysis Task Completion Phase

During this phase, both parts meet again:

- To discuss the results: findings and recommendations,
- To discuss the implementation of these results and recommendations,
- To discuss further analysis,
- To capitalize knowledge and gather lessons learned.

6.2 Workflow Analysis

Since it is assumed that the engineering design process, its phases, activities and sub activities are not known in advance, the first step is to fully describe the constitutive activities of the engineering design activities and/or the engineering design process on an operational level. Then the recurring interactions points described above can be reviewed in order to establish the workflow between both engineering design and design analysis activities. Finally, some further interaction points might subsequently be found that are specific to the task at hand.

If a similar notation of the activities as presented in Figure 1 for the GDA process model is also introduced for the engineering design 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.

If a traceability system is in place (see Section 6.1.2) 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.

7 Application

This example presents the evaluation of the frame structure of a device transportation system (DTS) developed for a semiconductor device, hereafter referred to as the “shipped device”; see Figure 4. The complete design of the DTS is presented in [ErBu-2005]. 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 4 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.

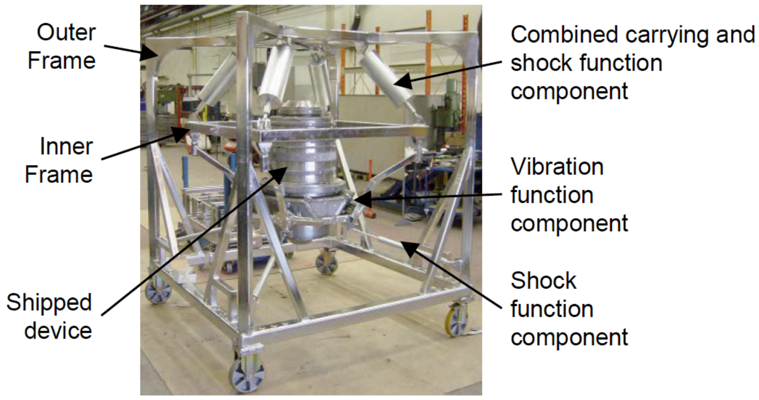

Figure 4: Overall description of the shipped device as well as the DTS (courtesy Validus Engineering AB)

In the following description of the industrial case, the main interactions between engineering designers and design analysts are numbered within parenthesis. The information workflow of these interactions are represented in Figure 8. The sub activities of the GDA process model that were not relevant for this particular project were removed.

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 (multi-body system, MBS, and finite element analysis, 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 within the company.

A pre-study of various working principles with an established MBS computational model (as shown in the left picture in Figure 5) was performed in order to assess the demand on acceptable acceleration levels. The engineering designer provided input on spatial space available as well as expected volume of the shipped device taking mounting design into account. The outcome of this pre-study was communicated to the project team (2) after which the engineering designer developed the principal frame structure layout. Based on the pre-study the decision was also taken to initiate a subsequent design analysis task of the frame structure (3). The engineering designer acquired in collaboration with suppliers characteristics of the load carrying and shock function components as well as input to the properties of the outer box such as representative boundary conditions. The engineering designer then provided these elements to the design analysts. 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 mutually between the engineering designer and the analyst, which is the included in the task content brief (4). The initial FEA computational model was established as shown in the middle picture in Figure 5. The frame was given only principle beam properties and geometrical layout in order to represent the needed volume of the solution with regards to the movement required as described by the MBS analyses results. The principle frame data were established and refined during an iterative design analysis process in which the MBS forces were transferred into the FEA where the structural response was studied. The objective of the analyses was to find some overall geometrical beam data that would be feasible from a material yield strength perspective.

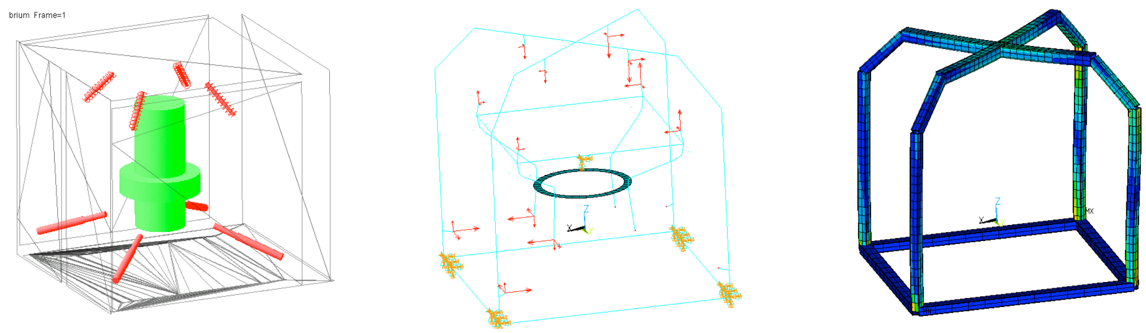

Figure 5: Presentation of the initial MBS and FEA models as well as the FEA results (courtesy Validus Engineering AB)

The results, as shown in the right picture in Figure 5, 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 linear to non-linear characteristics. This information was included in an updated task content brief (6) that was discussed. In the meantime, the engineering designer investigated and analysed preferable profiles and dimensions based on availability and cost and then provided these data as an input to the updated task content brief. The updated task content brief was 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 designer, the updated task content brief forming the basis for the FEA analysis (8). Figure 6 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, developed by the engineering designer, were also included in order to incorporate them into the complete system being studied.

In Figure 7 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 6) it can be seen that the fourth layout has the overall lowest stress levels during collision.

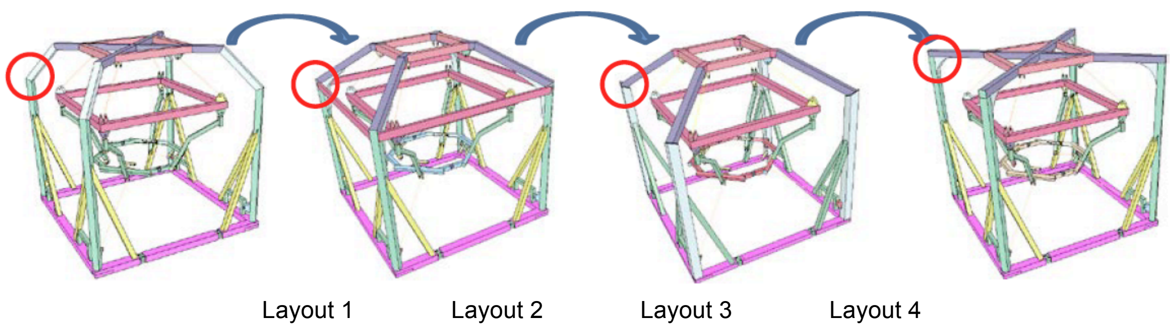

Figure 6: Preliminary layouts for the DTS (courtesy Validus Engineering AB)

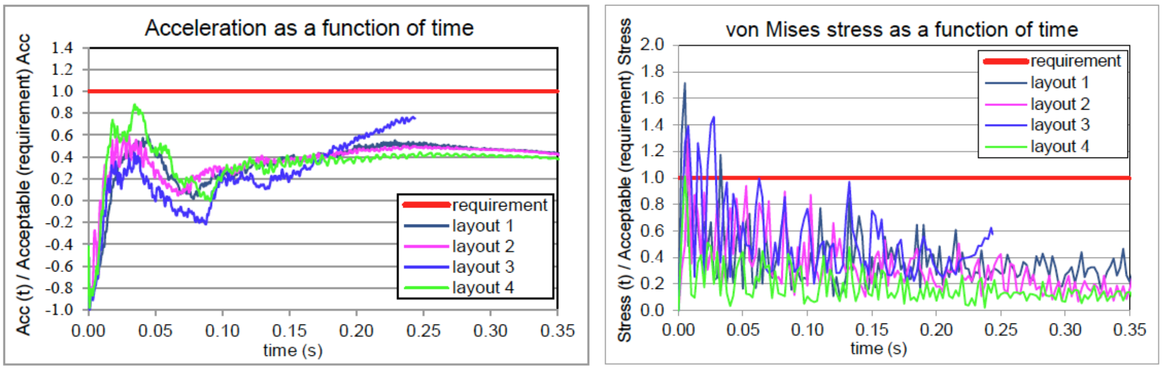

Figure 7: Comparison of results from the different preliminary layouts of the DTS (courtesy Validus Engineering AB)

During the results interpretation it was concluded that the fourth layout also generally performed better than the other layouts when studying the other load cases included in the product specifications. Additional assessment performed by the engineering designer regarding manufacturability and ease of assembly as well as component selection and fastener designs not explicitly included in the design analysis. 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).

8 Discussion and Conclusion

In addition to the application example accounted for above, the approach has been successfully utilized in industrial projects, such as: *Explorative analysis* of a bumper beam system with the objective to identify important design parameters associated with an existing predefined design solution; *Physical testing* of the DTS (above) during which design analysis tasks were carried out with the objective to facilitate the application of measurement systems by establishing positions and other measurement parameters related to the actual testing activity; *Method development*, that is, the development of design analysis guidelines and procedures with the objective to facilitate for the engineering designer to actively participate in parts of the design analysis activities as well as to improve the performance of the analysis process. The nature of these diverse projects indicates the relevance and validity of the proposed approach, which facilitates an increased interaction at an operational level between engineering designers and analysts.

An additional aspect of importance is the flexibility of the handling of integration between the engineering design and the design analysis processes. This is accommodated by allowing for the diversity of engineering design processes utilized in industrial practice.

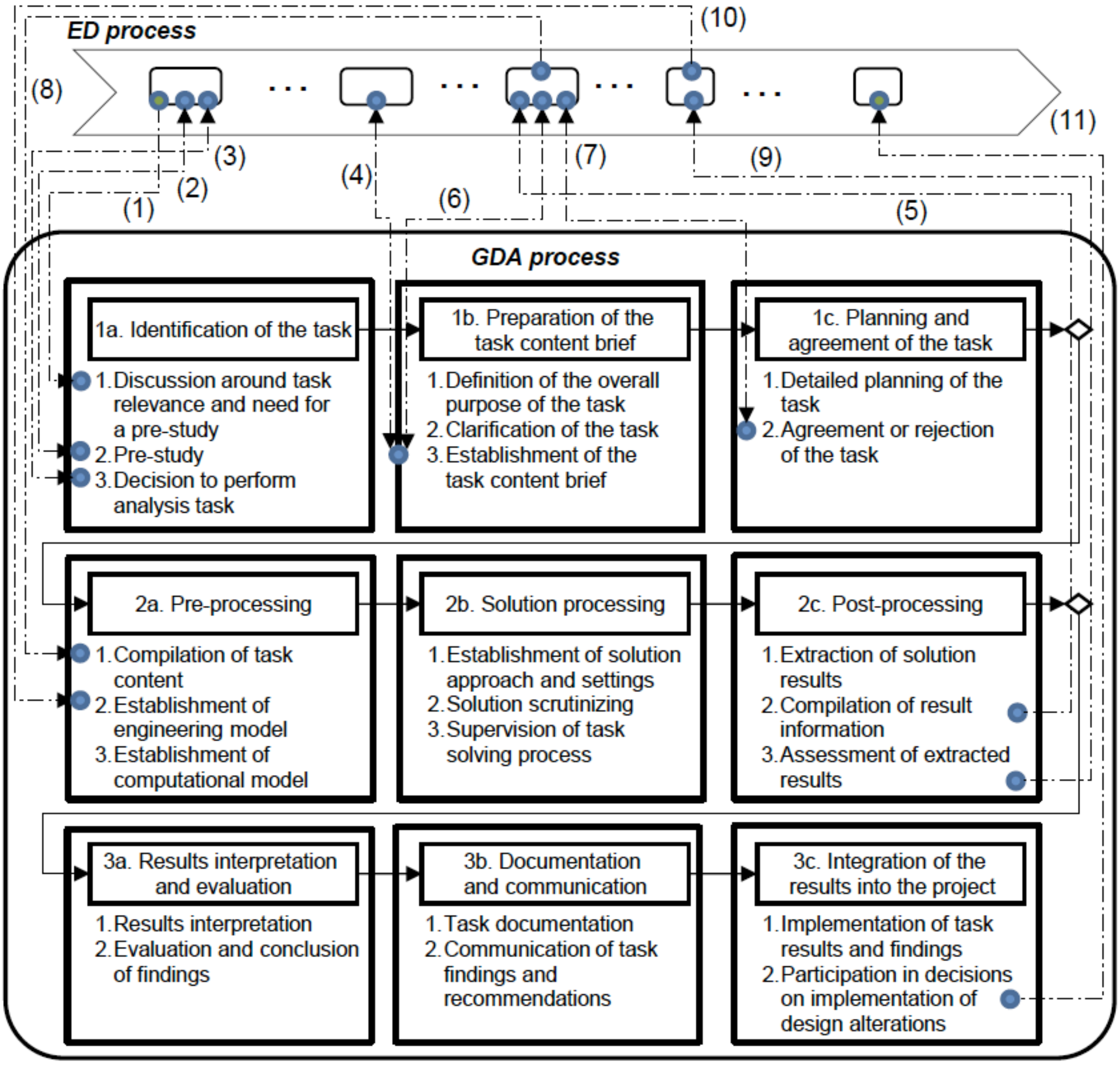

Figure 8: Workflow during the evaluation of the outer frame of the DTS

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