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AN INTEGRATIVE DESIGN ANALYSIS PROCESS MODEL WITH CONSIDERATIONS FROM QUALITY ASSURANCE

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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

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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 Vandepitte, 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 specified 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).

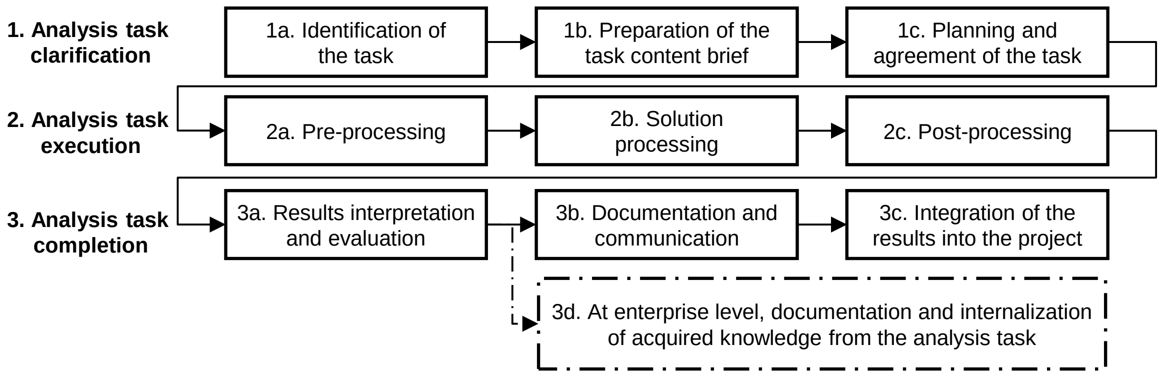

Figure 1. Overall design analysis process model with defined activities and steps.

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.

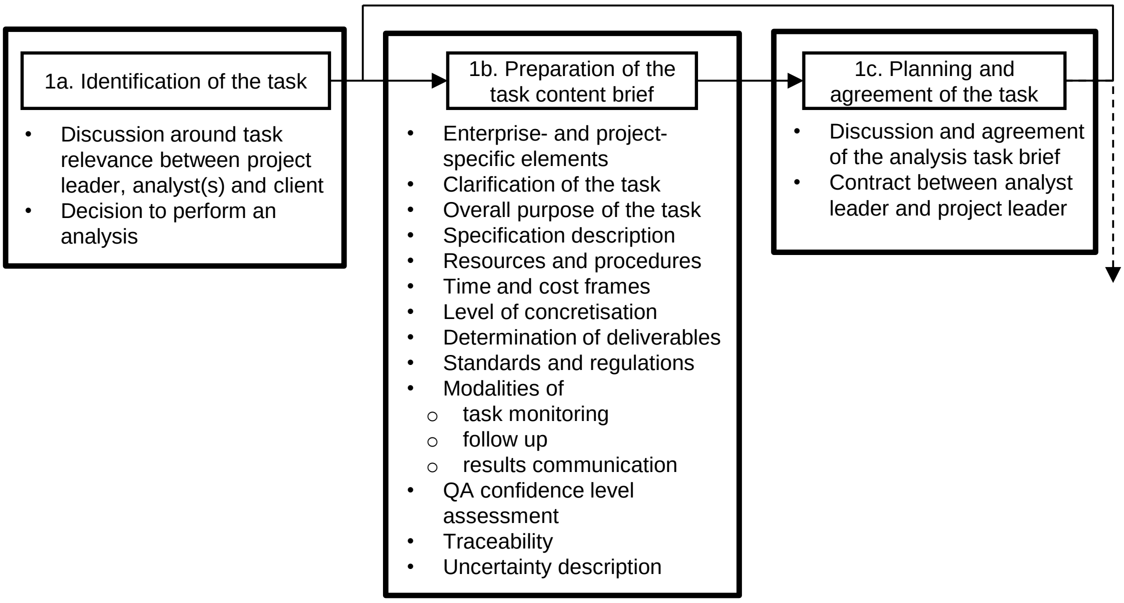

Figure 2. Analysis task clarification steps

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.

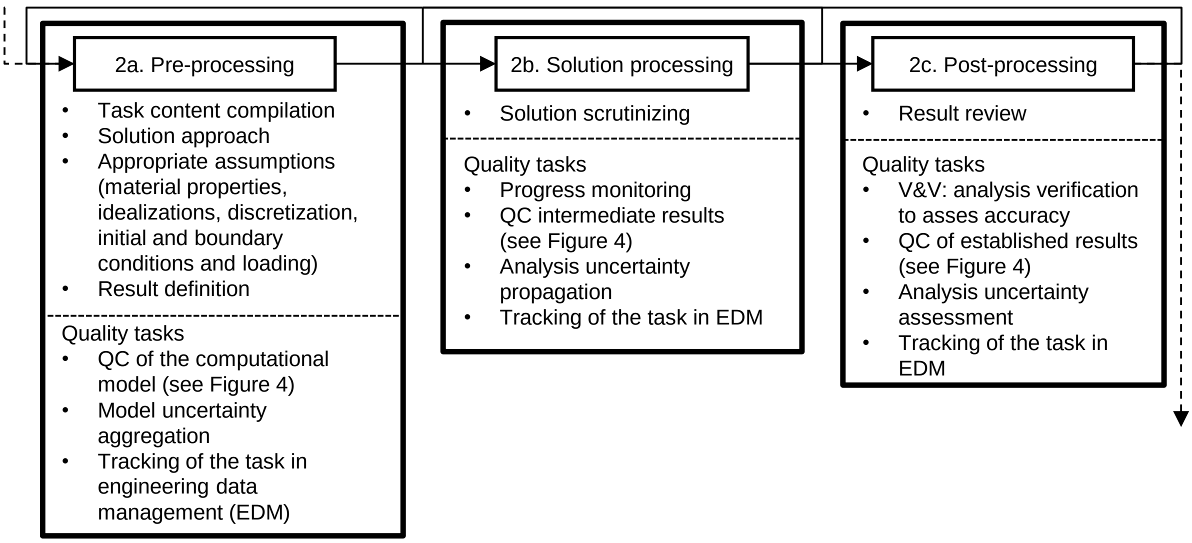

Figure 3. Analysis task execution steps

The model creation within *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. The *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.

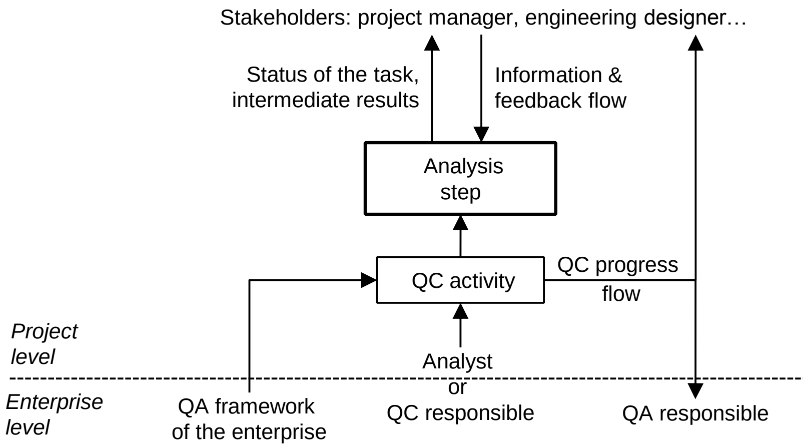

Figure 4. Solution processing step task monitoring and quality checking

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 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 view point. 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.

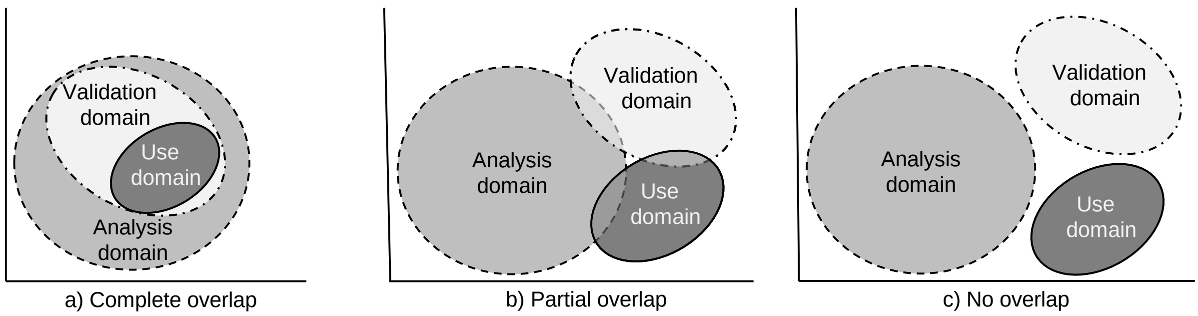

Figure 5. Relationships between analysis, validation and use domains linked to validation. Adapted from (Oberkampf et al. (2004)

Uncertainty quantification. The findings within the assessment of uncertainty propagation in the 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 mathematical values 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 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 the project team with 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.

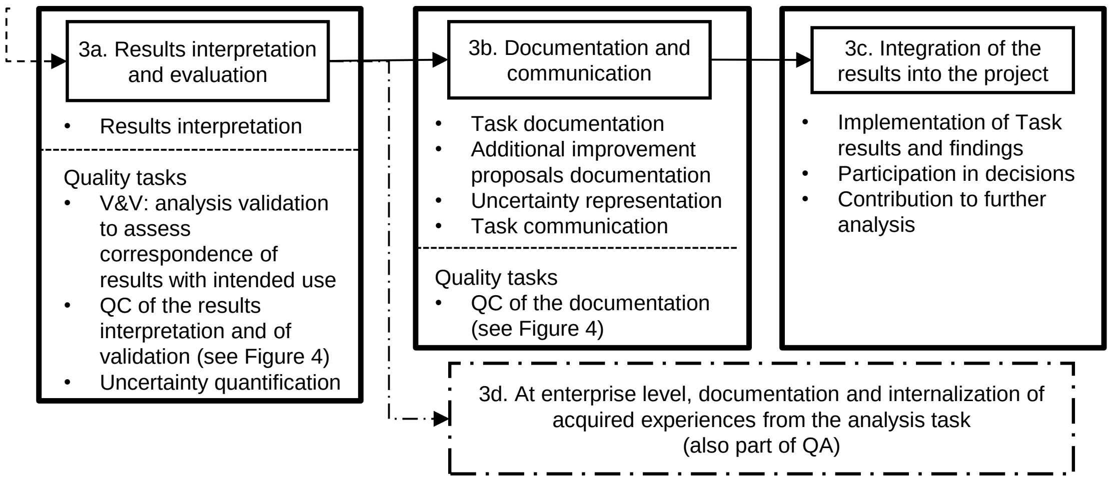

Figure 6. Task completion steps

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.

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