# Integration of the computer-based design analysis activity in the engineering design process - A literature survey

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

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## ABSTRACT

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

## KEYWORDS

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

## 1. INTRODUCTION

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

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

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

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

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

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

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

## 2. METHOD

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

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

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

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

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

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

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

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

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

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

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

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

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

## 3. GENERAL TOPICS OF THE REVIEWED PUBLICATIONS

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

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

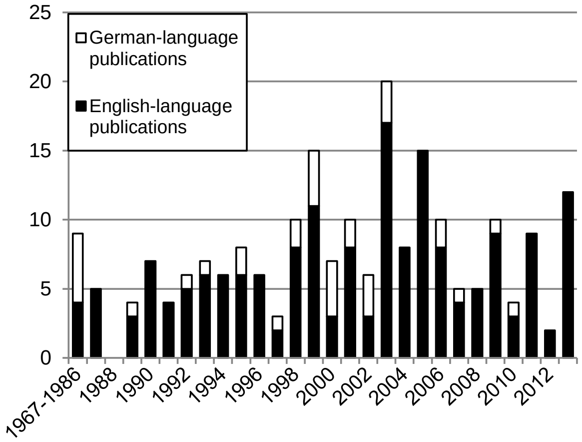


**Figure 1** Number of publications per year

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

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

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

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

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

## 4.1. Integration in general process models

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

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

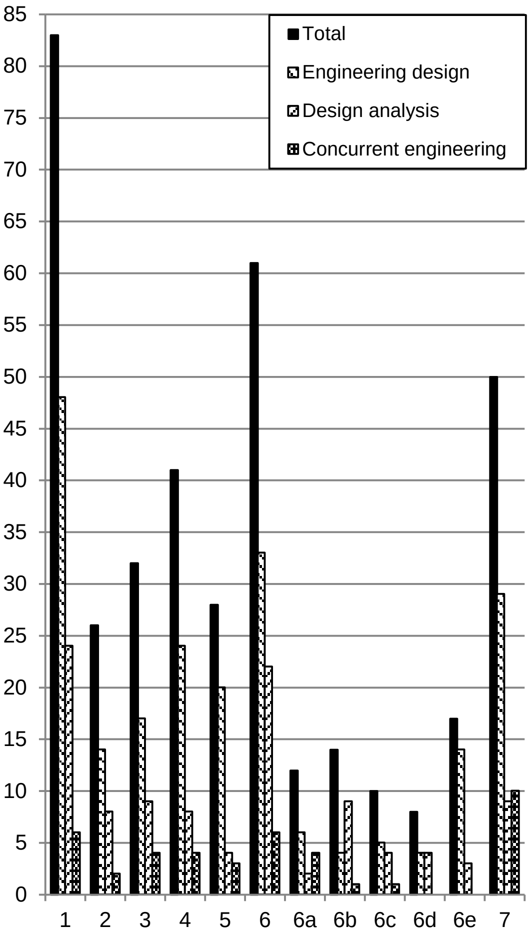


**Figure 2** Number of publications per identified topic. The 12 non-classified publications are included in the Total column

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

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

## 4.2. Accounts and reports from industry

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

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

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

## 4.3. Recommendations for the different analysis activities

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

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

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

## 4.4. Analysis early in the engineering design process

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

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

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

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

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

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

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

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

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

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

## 4.7. Others

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

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

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

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

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

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

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

## 5. DISCUSSION AND CONCLUSION

### 5.1. State of the literature

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

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

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

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

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

## 5.2. Key recommendations from the literature

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

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

## 5.3. Further domains of enquiry

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

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

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

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

## 5.4. Perspectives

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

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

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