Application of Design Models in Mechatronic Product Development and Building Design – Reflections of Researchers and Practitioners

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Design models are an essential means for abstract representation and visualisation of information in the design process. Comprehension of design models in interdisciplinary engineering design teams is often hindered by different terminology and different discipline-specific modelling approaches. This paper presents the results of an interview study conducted with practitioners and researchers from engineering design and building design. The study elaborates the different ways of collaboration and use of design models in building design as compared to engineering design, in order to derive the potentials for cross-fertilisation between both areas of product development.

Keywords: interdisciplinary product development, design models

1 Introduction

The aim of design research is to provide industry with methods, tools, recommendations, and approaches to meet the challenges arising from worldwide competition and increasing consumer-awareness, resulting in more complex, rapidly changing requirements and user-expectations [1]. The increasing product functionality expected by the user more often requires interdisciplinary collaboration of different experts to develop integrative solutions [2, 3]. In order to optimally co-ordinate individual design activities in (interdisciplinary) product development projects and to ensure each designer to be working towards a common goal, Valkenburg [4] stresses the importance of establishing what she refers to as "a shared understanding" of both the addressed problem and the design objective among collaborating designers. This includes e.g. the product requirements, the required functionality, and alternative (interdisciplinary) principle solutions. However, while no physical object has been produced, the product in development only exists in the designers' minds and is externalised, stored, and elaborated through using design models (after [5]) – such as sketches, drawings, physical or functional models [6–8].

1.1 New challenges

In general, so far, existing modelling approaches are essentially discipline-*specific* and use of design models *across* disciplines, hence, is often hindered by different terminology, different modelling approaches, and lack of knowledge about other disciplines [9]. This research focuses on engineering design of mechatronic products (as the combination of mechanical engineering design, electrical engineering design, and software development) as the most common interdisciplinary product development in industry. Although Buur [10] strongly emphasizes "*that in fact* […] (mechatronic product development) *must be regarded* […] *not just as a combination of traditional engineering fields, in order to exploit the full potential of* […] (their) *symbiosis* […]" the *integration* of all the essential discipline-specific perspectives (in modelling and designing) is not sufficiently supported in literature and has not sufficiently been addressed in research [11]. As will be discussed in more detail later on, even the development of large complex products, e.g. in robotics or aerospace industry, shows essentially separate discipline-specific design strands. To overcome this situation, the establishment of a "shared understanding" and the integration of discipline-specific perspectives among involved designers, needs to be supported by design research, e.g. through linking discipline-specific modelling approaches.

1.2 Integrative perspective on design

Another area of interdisciplinary product development is building design, as the combination of architectural design, civil (or structural) engineering design, and building services engineering design. Looking into building design may be used to apprehend inspiration from another area of product development to support modelling across classical engineering design disciplines. Albeit building design is not solely focused on the development of technical products – other than engineering design – the comparability of both areas is frequently discussed in literature. Roozenburg and Cross [12] state, that models of the development process – especially in the nineteen-sixties – showed significant similarities in both areas, but have grown apart starting from the early nineteen-seventies. In their view, process models in engineering design now put a stronger emphasis onto the "vertical" – linear, procedural – dimension of design projects, while "*in* […] (building design[1]) *the attention* […] *has shifted* […] *to the horizontal – iterative, problem-solving dimension*" [13, p.217]. It is their belief that both dimensions need to be converged, as they are merely two different perspectives onto the same thing and both dimensions are needed within product development: "[…] *it is obvious that all designers need to progress their projects in a sequence of stages* […]; *it is also obvious that designers must employ varying cognitive procedures during the design process*" [12, p.218]. Daly [14] and Goel and Pirolli [15] share this line of thought. Focusing on the problem-solving character of product development Goel and Pirolli argue, that disciplines like architecture and mechanical engineering show "*significant commonalities in the structure of design problems and tasks across the various design disciplines* […]" and that therefore design needs to be studied "*as a subject matter in its own right, independent of specific tasks or disciplines*" [15, p.398]. Eckert and Clarkson [16] similarly argue that design in different disciplines may differ in their emphasis put onto specific aspects, but show essential similarities across disciplines on an abstract level.

Regarding the similarities on a high level of abstraction across disciplines, Gericke and Blessing [17] come to a similar conclusion. However, they propose that a generic consensus model of product development not only needs to integrate the two dimensions of design projects, discussed by Roozenburg and Cross [12], but also needs to be sufficiently adaptable to different product development contexts and tasks. A recent example from research, to suggest that building design and engineering design are indeed very similar, is the 2-dimensional process model by Zeiler and Savanovic [18]: the "general systems theory based integral design method". Albeit the method is based on various product development approaches in German and Anglo-American literature from engineering design and general systems engineering, it has successfully been taught and applied in an architectural environment [19].

[1] Roozenburg and Cross [12] generally refer to it as „architectural design", while in fact addressing the entire process of designing a building.

1.3 Collaboration in design

Besides these more general considerations regarding the comparability of building design and mechatronic product development, Eisenbart et al. [20] discuss various generic design states[2] across disciplines based on a detailed analysis of the design models proposed in literature from mechatronic product development (including the involved engineering design disciplines) and building design. Within a generic design state, the proposed design models address similar information across disciplines. However, literature [22-24] suggests that the way different experts collaborate with each other within the product development process differs essentially between both areas, as shown in Figure 1. [22, 23] propose that different (discipline-specific) sub-systems of the overall mechatronic product are typically developed in parallel by separate groups of designers. In building design, different phases of the design process usually involve different people: concept development is usually carried out by architects, while structural engineers and building services engineers are typically more focused on embodiment and detail design [24].

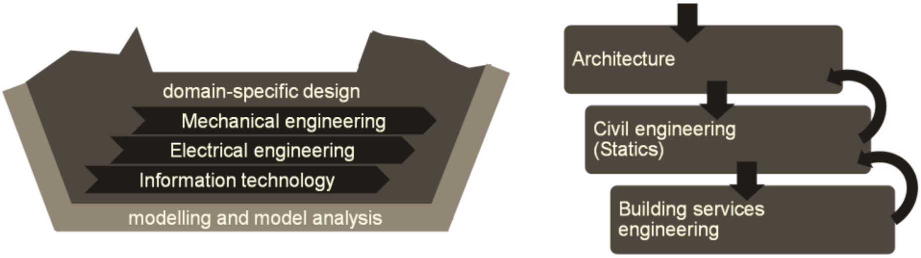

Figure 1: different collaboration in mechatronic product development (left, after [23]) compared to building design (right, after [24])

1.4 Research need

As discussed above, in engineering design integrative modelling approaches to support communication within a joint development project have not sufficiently been established. This may be due to the fact that the involved sub-disciplines have originally evolved as autonomous design disciplines and discipline-specific sub-systems of a mechatronic product are often

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[2] The term *design state* (after [21]) denotes the incorporation of all information about a product – which is stored within the sequentially developed design models 6 – as it evolves.

developed widely separated from one another. Since individual designers in building design operate sequentially, communication between experts is *essential*, requiring the exchange of all the relevant information at handover. Considering these different ways of collaborating, it can be assumed that the use of design models to support communication will also differ significantly between both areas. Moreover, as the different experts in building design have always been obliged to collaborate in order to develop a building in its entirety, it can further be assumed that modelling approaches in building design facilitate the integration of discipline-specific perspectives. Based on these assumptions it is expected to be beneficial to investigate:

- What are the implications of the different uses of design models regarding the problems of integrating discipline-specific perspectives in mechatronic product development?

- What are the potentials for cross-fertilisation between both areas of product development?

2 Reflection of Researchers and Practitioners – an interview study

The presented explorative interview study has been conducted with experts from engineering design and building design, in order to contribute to a deeper understanding of the commonalities and differences between both areas. The findings are used to elaborate the potentials for cross-fertilisation between both areas of product development regarding integrative modelling approaches.

2.1 Study design

The interviews have been conducted with 16 researchers and practitioners from classical engineering design, including interdisciplinary (mechatronic) product development and building design. Table 1 illustrates the individual backgrounds and experiences of each interviewed expert in more detail. Participants have been interviewed once (in some cases twice) with each session lasting between one half and one hour. Focus was put onto

- Process of product development
  The interviewees were asked about the particular approaches to product development they experienced in practice or knew from literature (e.g. from research or education).

- Communication across disciplines
  The questions focused on the participants' experience with communicating across disciplines, regarding problems or successes and their opinion about the particular reasons behind success or failure of communication.

- Use of design models to support communication
  The participants were asked about specific design models which are typically applied within the development process, focusing on those used to communicate with others.

Table 1: Individual background and experience of each interviewee

Experts	**Educational background**	**Industrial experience**	**Business size**	**Research experience**
Mechanical engineering design	Mechanical engineering	Hydraulic system designer in Aerospace industry	Large	Model-driven hydraulic system development
	Mechanical engineering			Engineering design research
Electrical engineering design	Electrical engineering	Microchip development for measurement equipment	Small	
Software development	Computer Science			Computer tool integration
	Computer Science			Computer tool integration
	Computer Science	Program development	Medium	Model-driven engineering
Mechatronic product development	Mechanical engineering			Model-based mechatronic system development
	Electrical engineering, automation technology	Robotics development	Medium	Automation technology
	Space systems engineering	Systems integration in satellite design	Large	Design methodology research
	Production engineering	Conceptualisation of manufacturing machines	Large	Production engineering
Building design	Civil engineering	Structural engineering, bridge design	Small	Structural engineering
	Architecture	Bridge design	Small	Design research
	Civil engineering	Public construction project management	Small	
	Civil engineering	Residence construction project management	Small	Structural engineering
	Civil engineering			Structural engineering
	Civil engineering			Structural engineering

2.2 findings

Regarding the development process, engineering designers agreed with what has been suggested in [23]: it is generally an important endeavour in mechatronic product development projects to be working in parallel on different (discipline-specific) sub-systems. The classical sequential approach to building design described in [24] is still very common, but being challenged by two aspects of product development which – according to the interviewed construction project managers – have become more relevant in the recent past:

- More demanding climate requirements (legislation) – concerning both indoor climate as well as energy efficiency of buildings – impact strongly on concept development, thus requiring the collaboration of architects and building services engineers; but also – especially regarding façade design – structural engineers. Other examples are buildings with a strong linkage between shape and statics (e.g. bridges – demanding collaboration between architects and structural engineers) or with high spatial and functional demands (e.g. hospitals – requiring collaboration of architects, structural engineers, and building services engineers) as space, room equipment and indoor climate management need to meet specific requirements.

- Project managers stated to be making an effort themselves to involve structural engineers and building services engineers earlier in the process. Leading concept development in "the right direction" regarding e.g. dimensions and position of pillars or the position of breaks through walls for pipes and cables, has often helped reducing the number of iterations and development time in the overall process considerably.

Table 2: Comparison of the development process

		Building design	**Engineering design**
development process	development strategy	sequential	parallel, widely integrated approach
		product-oriented approach in practice	mostly product-oriented approach, depending on corporate culture
		some approaches to spacial decomposition	decomposition essential, important tool of interdisciplinary product development
	experts involved in concept phase	most of the time one/ few architect(s)	experts from various disciplines involved
	application of design methodologies (or systematic approaches to design) in practice	few; various adaptations from project management	few but increasing, depending on the particular corporate culture
	production quantities	always a "one-piece production"	(mostly) great number of units to mass production
	estimated product life time	very long	(mostly) short to medium
	influences on the product development process	strongly influenced by cost estimates, aesthetics; product design very often artistically driven	costs, functionality, corporate culture

Each interviewed designer with a background in industry independently stated industrial product development to be characterised by severe shortage of time and far-reaching financial restraints. Most engineering designers stated to know about systematic, methodical approached to product development from literature, but rarely recalled them being applied in industry. However, one of them described that in one company he has been working at, it has regularly been attempted to introduce more methodical approaches to product design. To his knowledge – so far – without success. In building design with only one exception none of the interviewees could recall to have heard about methodical approaches or literature on systematic product development. Only the interviewed architect knew about these approaches, but only seldom applied them in his daily work in industry. Further findings regarding the development process have been summarised in Table 2.

Communication across disciplines differs considerably between engineering design and building design. While interviewees from engineering design generally stated to have essential problems understanding design models and terminology used by collaborating designers with a different engineering background, participants from building design did not report about having these problems. The only problems that were mentioned result from what is here referred to as "social factors": One construction project manager described the collaboration on large construction sites occasionally to be characterised by conceit of some architects towards the involved technicians, including reluctance to discuss specific details of their concept or to accept suggested changes. Engineering designers themselves see the reasons for the communication problems mostly originating from the lack of knowledge about the design models used within the other involved disciplines. Table 3 summarises the discussed findings.

Table 3: Comparison of communication within the development process

		Building design	**Engineering design**
communication	Communication problems	few	yes
	Communication problems caused by different ways of modelling	no	yes, partly leading to fundamental misunderstandings or termination of discussions
	Other reasons for communication problems	overall-view versus detail-view; "social" factors"	different terminology, lack of knowledge from the other discipline, different perspectives (dimensions, stresses versus signal flows versus procedures)
	Reasons for understanding/ misunderstanding	use of common "pictograms"	no/ few common modelling approaches
	exchange with collaborators	in project/ design meetings	in design meetings; short, frequent tête-à-têtes with colleagues

In building design the designers often seem to use specific, what is here referred to as, "handover documents" as well as legal documents (e.g. to apply for permits) to support the exchange of information. The interviewed building designers stated that the architect(s) will have to create a particular set of drawings and sketches – with a specific level of detail – as well as textual descriptions to hand over to the structural engineer(s). The building services engineer(s) receives another set of particular documents from the structural engineer – on a more detailed level – to work with. According to the two construction project managers these documents also typically mark the end of one main development step and contain all the relevant information. Taken from the description of the participants it seems that the diversity of documents used in engineering design generally is much higher than in building design, which mostly seem to rely on 2-dimensional representations.

Table 4 gives a brief overview of the gathered findings.

Table 4: Comparing the use of design models within the development process

		Building design	**Engineering design**
design modelling	Specific design models for communication purposes	sketches, drawings, specific "handover"-documents, with a specific level of detail	great diversity, strongly dependent on design project
	type of models used	essentially 2-dimensional visualisations, 3-dimensional visualisations or physical models only for presentation to customer	great diversity, for customer, colleagues, for oneself etc.
	essential design models for the different phases of product development	process typically moves from one handover document to the next, which also marks individual phases [3]	models are used to generate, evaluate, simulate etc. every new piece of information gained is thus stored in design models

3 Discussion

Literature discussed in the introductory chapter suggests that from an abstract point of view building design and engineering design can be regarded as very similar. The conducted interviews indicate that numerous differences exist on a more concrete level regarding the particular way product development is carried out. Most importantly, however, the conducted interviewees confirmed the communication processes supported through design modelling to differ substantially between both areas. As assumed, the different ways of collaborating – in building design as compared to engineering design – have an essential influence on communication and the use of design models to support the exchange of information. Parallel discipline-specific design, as it is common practice in mechatronic product development, requires continuous communication of relevant changes made within each sub-system. However, comprehension of discipline-specific design models – and therefore communication across disciplines – is often hindered. In contrast, building designers do not seem to have any problems. This supports the assumption, that design models in building design are able to integrate the different discipline-specific perspectives onto the product in development.

According to the reflections of the participants, the classical sequential approach in building design derived specific handover documents to support the exchange of all information relevant to the other experts. These seem to be generally understandable across disciplines. The interviewed engineering designers did not describe anything similar. However, apparently, it is not only due to these specific handover documents, that communication is successful in building design, as even in a parallel development project, there seem to be no problems understanding the used design models across disciplines. This may be due to the shared pictograms as well as the low diversity of the used design models within the development process, as compared to engineering design. Moreover, from the used design models mentioned by building designers, it seems that the *shape* of the product represents a shared aspect in their individual perspectives onto product design. It remains unclear if such a shared view exists across all involved engineering design disciplines in mechatronic product development. The interviewed engineering designers did not recall something similar from their experience.

4 Conclusions

The use of design models to support the exchange of information between engineering designers is essential. The integration of discipline-specific perspectives in a mechatronic product development project, however, is often hindered, due to a lack of shared terminology and integrative modelling approaches. Building designers, in contrast to engineering designers, have always been obliged to handover all the relevant information to other experts within the development process. It could therefore assumed, that the use of design models differs between both areas and that design models used in building design are more suitable for facilitating the integration of discipline-specific perspectives than those from engineering design. Based on these assumptions, the study aimed at investigating the implications of the different use of design models regarding the potentials for cross-fertilisation between both areas.

The reported findings strongly support the assumptions and it is expected that a more detailed analysis of modelling approaches in building design may help develop recommendations or modelling approaches to support interdisciplinary product development in engineering design. It seems, two key factors for successful communication in building design are the lower diversity of design models used to support the exchange of information and use of shared coding (pictograms). However, even though building designers use shared coding and modelling approaches to support the exchange of information, it is clear that this is not easily transferable onto engineering design. Shared coding and shared representations (i.e. visualisations) of mutually relevant information – so far – have not been established in engineering design. Future work needs to elaborate in detail, how the representation of relevant information is facilitated in modelling approaches from building design and to which extent these can be adopted to engineering design.

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