COMPARISONS OF DESIGN METHODOLOGIES AND PROCESS MODELS ACROSS DISCIPLINES: A LITERATURE REVIEW

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ABSTRACT

Challenges resulting from an environment characterised by complexity, competition on global markets, dynamics and ever-changing user wants and needs are increasing and affect all design processes, irrespective of whether the product or system designed is a machine, a building, software, service, etc.. These challenges require collaboration between disciplines, but current design processes of large systems, such as aircraft, essentially show separate development strands for each discipline. Research into methods is ongoing, but the original design methodologies have not been adapted accordingly.

Based on a literature study this paper consolidates findings from different comparisons of design methodologies and process models across disciplines. A consensus can be found that at least on an abstract level design process models have a generic core of common stages. On a detailed level the picture is different. The extent to which design approaches appear similar depends on the perspective of the analyses.

The literature study provides an overview of shortcomings of existing design methodologies which may serve as starting points for further research and development of design methodologies.

Keywords: design methodology, process models, multidisciplinarity, collaboration

1. INTRODUCTION

Design research aims at supporting industry by providing methodologies, methods, tools and recommendations for designers to cope with the challenges resulting from an environment characterised by complexity, competition on global markets, dynamics and ever-changing user wants and needs [1]. These challenges are increasing and affect all design processes, irrespective of whether the product or system designed is a machine, a consumer good, software, a building, electronics, service, etc..

To rationalise creative work, to reduce the likelihood of forgetting something important, to permit design to be taught and transferred, to facilitate planning, to improve communication between disciplines involved in design, etc., was motivation for many researchers to develop prescriptive or normative models of the design process, the so called design methodologies, to support designing. A *design methodology* is “a concrete plan of action for the design of technical systems (…). It includes plans of action that link working steps and design phases according to content and organisation.” [2] The action plans are supported by methods. Many methodologies are based on the experience of the authors and examples of good practice [1], rather than on empirical studies.

Some of the early work on design methodologies took place in architecture [3, 4] but never established itself in practice. In mechanical engineering a considerable amount of work took place in the 60s, 70s and early 80s [5, 6, 7, 8, 9, 10, 11, 12]. Some of this work was further developed and only recently new work appeared, albeit strongly based on the earlier work [2, 13, 14, 15, 16, 17]. An overview of the historic development of these methodologies can be found in Heymann [18].

Methodologies for developing software are from a later date [19, 20, 21, 22, 23, 24].

Design methodologies are often taught, at least in the US and Northern Europe, but the industrial uptake of the methodologies has been limited and many remain unknown. However, some of the underlying concepts did find their way into practice and had a profound impact on design processes in industry [25].

New challenges

Increasingly demanding users, increased environmental awareness, as well as technological developments have expanded the original problem space to include several issues more explicitly: user issues, environmental issues, increased product functionality and complexity [16, 26, 27].

Research into methods to support these concepts is ongoing, but the original methodologies have not been adapted accordingly.

The expansion of the problem space requires new approaches and the adaptation of existing ones. Other disciplines may provide potential solutions, for example because of the specific features of their products. Civil engineering may provide approaches to deal with the separation of development and production. Software and knowledge based engineering may provide approaches to include user issues more explicitly. The abstract, function-oriented approach in software and electrical engineering may provide solutions to deal with mechanical systems at a more abstract, functional level.

The expansion of the problem space also requires collaboration between disciplines, but current design processes of large systems, such as aircraft, essentially show separate development strands for each discipline.

The necessary shared understanding of design processes can be supported by integrating or linking the approaches of different disciplines. Generally, however, existing design methodologies and methods are essentially mono-disciplinary. Exceptions are a methodology for the design of mechatronical systems [28] and some initial support for the development of Product-Service-Systems (PSS) e.g. [29, 30].

Research need

In our view, it is in particular the lack of understanding of the different design processes and of the differences and communalities of the various methodologies and methods to support these processes, which hampers the development of a transdisciplinary approach. A comparison of approaches in different disciplines and a rethinking of concepts are necessary.

This paper aims to consolidate and to contrast existing findings and insights provided in literature in order to identify areas were consensus can be found, areas were results are conflicting, and areas which were not yet sufficiently studied.

2. PERSPECTIVES ON DESIGN

Design disciplines

Goel and Pirolli [31] criticise the too simplistic categorisation of design as a problem solving activity which was proposed mainly by cognitive scientists. They argue that the lack of a clear description of design activities causes a proliferation of design related disciplines and activities.

As an attempt to further specify what a design activity distinguishes from other activities, Goel and Pirolli differentiate between design and nondesign problem solving. They characterise design problem solving as a radial category of problem solving. This categorisation does not lead to a clear distinction between design and nondesign disciplines but into disciplines which are rather prototypical (or central) to design than others.

Goel and Pirolli [31] argue that disciplines prototypical to design share commonalities e.g. regarding the structure of design problems and that design problems differ much from non-design problems. "We assume that there are significant commonalities in the structure of design problems and tasks across the various design disciplines, and there are significant differences in the structure of design problems and nondesign problems. As such, we make a strong commitment to the study of design as a subject matter in its own right, independent of specific tasks or disciplines." [31, p. 398]

Goel and Pirolli [31] state that disciplines such as architecture, mechanical engineering and instructional design are prototypical for design problem solving.

Design as a discipline of its own

Daly [32] pursues this line of thought. She describes design as a discipline of its own. She argues that existing definitions of design, independently whether design as a verb, a noun, as a phenomenon and as an activity, cover only specific aspects and do not capture design as whole.

Based on a phenomenological study of examples from different disciplines (chemical engineering, dance composition, architecture) she categorises different descriptions of what design is in a hierarchical manner: *Decision-making*, *Translation*, *Synthesis*, *Progression*, *Exploration*, *Freedom*.
“Most closely related to this study's findings in the literature is the definition of design as an approach. The way that designers understand - implicitly, explicitly, and tacitly - what it means to design has an impact on how they will approach a design task […].” [32, p. 129]
This implies that different approaches to design can be found but the differences are not necessarily related to the discipline but to the way the designer interprets design.

Patterns of designing

Eckert and Clarkson [25] propose a different perspective for the analysis of design across disciplines.
They state, that despite “all design processes are different” the processes show on an abstract level many similarities across disciplines, but differ for example by the emphasis put on specific activities. These similarities of design processes are caused by common drivers. Such elements of process behaviour are called patterns of designing.
Eckert and Clarkson argue that researchers should focus their studies on patterns of designing, in order to understand design processes better and be able to improve them accordingly.
“A pattern is not just any ‘chunk’ of a process, but something that is recognised as a recurring event and hence has a meaning beyond the single instance.” [25, p. 20]

3. MODELLING THE DESIGN PROCESS

Stages, activities and strategies

Process models are a central element of design methodologies. In order to provide a consistent terminology for a comparison of process models Blessing [1] proposes to distinguish between stages (often called design phases), activities and strategies:

- A *stage* is defined as a subdivision of the design process based on the state of the product under development. Every stage may cover a considerable period of time.
  In general, three stages can be identified in most models: a problem definition stage (set of requirements), a conceptual design stage (concept of solution principle) and a detail design stage (full product description)
- A design *activity* is defined as a subdivision of the design process related to the individual's problem solving process. It is a much finer division than a stage, covering a shorter period of time. A typical characteristic of an activity is that it reoccurs several times in any one process. Examples are: generating, evaluating and selecting.
  Blessing [1] identified five types for representation of design activities in prescriptive process models: hidden, recurring type I&II and independent type I&II. These are related to the strategies.
- A *strategy* is defined as the sequence in which design stages and activities are planned or executed. The strategies represent possible ways to execute the design process, e.g. stepwise, cyclic, decomposing, iterative and abstracting/concretising.

Classification scheme

Based on a review of design process literature Wynn and Clarkson [33] propose a classification scheme. Based on the work of Lawson [34] and Blessing [1] they distinguish the literature on design approaches, which provides models of the design process, in three different dimensions (see Figure 1).

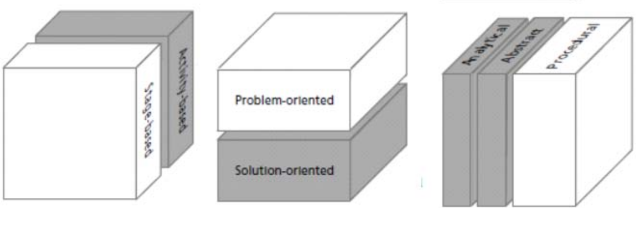

Figure 1: Classification of design process literature [33]

Design process models can be distinguished by the emphasis they put on either design stages or design activities. While some process models are purely *stage-based*, i.e. structure the process in different stages; *activity-based* models represent the process by focussing on the activities [1, 33]. Some models combine both perspectives [1].
Design process models can be further distinguished into *problem-oriented* models and *solution-oriented* models (called product-oriented in [1]). "The problem-oriented models concentrate on analyzing the problem, and are characterized by abstraction steps. Product-oriented models put more emphasis on analyzing the product idea and are characterized by analysis and evaluation steps." [1] *Solution-oriented* models which place more emphasis on design management than on product design are less detailed than *problem-oriented* models [1].
Abstract approaches represent the design process at a high level of abstraction. *Procedural approaches* represent the design process on a more detailed level of abstraction highlighting specific aspects of a design process. *Analytical approaches* are different they are used to represent, analyse and improve specific aspects of design projects (e.g. by using dependency structure matrices) [33].
Wynn and Clarkson [33] further subdivide the class of procedural approaches into (see Figure 2):

- descriptive and prescriptive literature
- project and design focussed approaches

Procedural approaches contain process models and methods.

Figure 2: Classification of procedural approaches [33]

Design methodologies belong to the class of procedural approaches as they contain a procedural process model and methods. Therefore, design methodologies can be distinguished into project-focussed and design-focussed, and into descriptive and prescriptive.
According to Blessing [1] *descriptive* models represent good practice. They may be used in order to develop *prescriptive* models. *Prescriptive* models, which are usually based on a systematic or methodological sequence of design stages and activities, are considered to represent improved processes that are more effective and efficient than non-systematical design processes.
Design-focused approaches such as proposed by Pahl and Beitz [2] aim to support the design of better products by providing a prescriptive model of the design process and propose methods in order to support the designer during this process. *Project-focused* process approaches (e.g. [35]) differ because they are intended to support the management of a design project.

Based on their classification scheme, Wynn and Clarkson [33] conclude that:

- Activity-based process models can be problem- or solution-oriented.
- Stage-based process models are usually problem-oriented in nature.
- Solution-oriented models are supposed to be more realistic descriptions of designers' thought processes than problem-oriented models.
- Abstract process models are typically activity based.
- Abstract models of the design process do not explain the process of design and do not provide a support for the designer.
- Procedural process models are usually stage based and often problem-oriented in nature.
- The distinction of design models into descriptive and prescriptive is not useful and usually not clear because most models contain descriptive and prescriptive aspects.

General critiques on design process models

A key weakness of design process models is their difficult application to real design problems [33]. Most process models are too general to help project planning and to guide daily decisions. While most models of designing integrate an iterative component or the evaluation of the results they do not describe how to achieve fitness for purpose of the product. Although most process models are too general for easy application, they can be interpreted in a specific context, hence offering guidance [33].

Eckert and Stacey [36] discuss the prescriptive character of many process models, and their applicability in practice. They conclude that prescriptive models usually are not (and do not aim to be) an accurate representation of how a product development process will proceed but that these models are intended to provide guidance to the designer during product development and support interaction between designers in many ways. They argue that process models do not need to be totally correct in order to be useful because correctness does not guarantee usefulness, especially if correctness requires excessive effort for modelling [36].

They further state that the abstract character of prescriptive process models requires interpretation by designers which may cause misunderstandings because people will interpret a model differently because of their individual understanding of the context, their experience, differing assumptions and differing believes how the model has to be interpreted (as a mandatory specification of actions or as a guideline) [36].

In contrast to other authors Lawson [34] concludes that in literature is no consensus whether a common design process exists. In his opinion are common patterns of design process models across disciplines not necessarily a prove that design processes are similar across disciplines because process models such as the RIBA plan of work in architecture [37] often show only the sequence of realised results not how the designer works. He argues that the assumption of a logical and predictable order of activities in all design processes is wrong because there is no sequence of operations which guarantees success and as a consequence of this, that an adaptation of a proposed process-model according to the specific problem is necessary. Lawson concludes that the ability to manage this adaptation is one of the most important skills of designers [34].

4. ANALYSES OF PROCEDURAL APPROACHES

In the following, the results of a literature study focussing on analyses of procedural approaches will be presented. The found literature is grouped into comparisons (of which most include approaches from more than just one discipline) and criticism of current procedural approaches.

Differences and commonalities

In engineering design process models have converged into the model of the VDI 2221 guideline. Cross and Roozenburg [38] call it a consensus model. The consensus model is based on the systems engineering approach as proposed by Hall [39]. The emphasis on the vertical (linear, procedural) dimension of the systems engineering approach in the consensus model of engineering design causes misinterpretations by its users, which oversee the horizontal (iterative, problem-solving) dimension which was included by the authors of the consensus model [38].

Cross and Roozenburg criticise the consensus model as a weak and heuristic method. They argue that it is weak because it is mainly based upon weak knowledge derived from the experience of its authors. It is a heuristic method because it requires interpretation by its users in order to be properly implemented in practice and does not guarantee success [40]. They recapitulate that the consensus model does not specify in detail how to achieve the intermediate results which are prescribed. They write “... it is not a recipe. Instead it tries to organize the problem-solving behaviour of designers to such an extent that it is more effective and efficient than intuitive, unaided, unsystematic ways of working." [40, p. 216]

Cross and Roozenburg [40] analyse the relationship between work on design methodologies in architecture, industrial design and mechanical engineering over the past decades. They state that the early design process models from the 1960's and 1970's were similar. In the 1970's these similarities were criticised by design researchers with an architectural background. The critics focussed on the common view that designers should resist developing solutions in the beginning of the design process as represented in the common analysis-synthesis model of design which prescribes a problem analysis before solution synthesis starts. These critiques lead to the development of alternative process models for example Darke’s model [41] highlighting the role of a ‘primary generator’.

A further result of these critiques of linear, sequential design processes, which are based on an analysis-synthesis sequence, is that in architecture and industrial design no consensus model can be

found. Cross and Roozenburg state that although no clear consensus models has established so far, a ‘type model’ can be found possessing a spiral structure, considering the influence of prestructures, presuppositions or protomodels as source for solution concepts based on these, and considering the co-evolutionary development of the understanding of problem and solution. They conclude: “in architectural and industrial design the attention of the design researchers and practitioners has shifted from the vertical - linear, procedural - dimension of the design process to the horizontal - iterative, problem-solving - dimension." [40, p. 217]
Comparing the engineering design consensus model and the architectural ‘type’ model Cross and Roozenburg identified some differing characteristics (see Table 1).

Table 1: Comparison of characteristics of the engineering and architecture ‘type models’ [38]

Characteristics of the engineering models	**Characteristics of the architecture models**
• Assumes problems are (or can be) well defined	• Assumes problems are ill-defined
• Systematic, expert process	• Opportunistic, argumentative process
• Starts with problem-analysis; avoids preconceptions	• Starts with solution-conjecture; accepts prestructures
• Linear	• Cyclical (Spiral)
• Tree-like problem structure	• Lattice problem structure
• Prescriptive of design behaviour	• Descriptive of design behaviour
• Emphasizes the vertical dimension (linear, procedural) of Hall’s morphology of the systems engineering process	• Emphasizes the horizontal dimension (iterative, problem-solving) of Hall’s morphology of the systems engineering process

Despite the historic separation of process models from architecture and engineering both authors believe that a new consensus model which is suitable for both disciplines is needed. Cross [17] and Roozenburg and Eekels [14] published different interpretations of such models.

Blessing [1] analysed approaches from mechanical engineering. After analysing different prescriptive models she concludes: "Almost all prescriptive models of design share a common characteristic: they propose a stepwise approach (strategy) expressed as a sequence of stages or activities. Within this sequence several differences can be found."
She found that the distinction between the different stages is more pronounced in prescriptive than in the descriptive models.
Blessing [1] concludes that prescriptive models of the design process show substantial differences but have also several characteristics in common, such as a stepwise top-down, iterative approach, easing the monitoring of the design process and emphasising an problem analysis prior to solution generation. A major distinctive feature of prescriptive process models is their emphasis on problem or product.
Based on a comparison of prescriptive literature with descriptive literature Blessing [1] concludes that designers tend to follow a product-oriented approach; abstraction steps, generation and consideration of solution alternatives as proposed in problem-oriented models are usually not addressed. She further concludes that merging both types of approaches seems promising in order to develop better support in the future.

Finkelstein and Finkelstein [42] analysed literature on design methodology. They state that design methodologies represent in general the same basic process. They emphasise the need for a context dependent adaptation of design methodologies in order to unfold their full potential in practice.
While much of the literature on design methodology is influenced by systems engineering approaches, not all techniques from systems engineering are always transferrable. In systems engineering, design concept generation is not as detailed supported as required in other design disciplines [42].

Möhringer [43] analysed discipline-specific approaches (mechanical engineering, software development, electrical engineering) and transdisciplinary approaches (mainly from electro-mechanics and initial support for the development of mechatronical products) in order to identify approaches which are applicable for the development of mechatronical products.
He concludes that most prescriptive process models are rather abstract and do not provide the necessary support which is required in mechatronic product development. Möhringer states that most approaches are based on/similar to the VDI 2221 [13] or the V-model [28] from software engineering.

The Design Council [44] reviewed current process models for product development and related research results. They conclude that currently no process model is applicable to every design context. They further argue: “Our world is evolving so quickly that there may never be an ideal methodology or process." [44, p. 8]
Though, no process model is applicable in every design context, they agree to Eckert and Clarkson [25]) and Best [45] that a central core of generic stages exists, which are common to all disciplines. This central core needs adaptation to the project specific context (project specific constraints and drivers).

According to Maffin [46] the insufficient support of adaptation is one important reason for the limited acceptance of design methodologies in industry. He states, that as a consequence practitioners often develop own approaches which consider the context in which the product has to be developed but do not consider the support offered by prescriptive approaches. “... procedures usually address what is required to be done as distinct from how it should be done.” [46, p. 316]

Howard et al. [47] analysed several design process models mainly from mechanical engineering. They identified commonalities between these process models and mapped the process models with six generic stages (phases): establishing a need, analysis of task, conceptual design phase, embodiment design phase, detailed design phase, implementation phase. The stages identified by Howard et al. [47] cover a larger span of the product life cycle compared for example with those stages identified by Blessing [1]. It should be mentioned that not all of the models involved in the comparison of Howard et al. covered all of the identified common stages. Most of these process models assume a market driven product development process (market pull) as opposed to technology driven processes (technology push).
Howard et al. [47] also found some important differences between these models especially differences in representing creative stages of the design process in these models and differing emphasis on divergence and convergence during the design process. They [47] conclude that these idealistic linear representations of the design process are primarily suitable for educational applications and the management of product development processes by providing a basis on which to build a stage-gate process but do not sufficiently represent the creative process.

Diverse authors (for example [34, 40, 48, 49]) found in different disciplines that analysis and synthesis emerge together. This Co-evolution of problem and solution is a central pattern of designing.

Based on his personal experiences mainly in computer science and architecture Brooks [50] concludes that design processes have constants across design disciplines. He observed many similarities across the disciplines such as the mental processes, human interactions, iterations and constraints of the process. He states that engineers have a clear (sometimes implicit) model of their design process. These are often influenced by procedural approaches, for example Royce’s Waterfall Model and the VDI 2221 guideline. Brooks calls such models rational models. According to Brooks these rational models of the design process have some important advantages compared to any unsystematic approach to design. However, these advantages require a critical use of these models, because their often observed unreflected (naive) application might cause problems, because these models are idealistic pictures of the design process [50].
Brooks [50] contrasts rational models with other models of the design process such as the Co-Evolution Model [48] and the Spiral Model [21]. According to Brooks the visual representation, its simplicity and the emphasis on the alternating focus of the design process on either the problem or the solution are positive aspects of the Co-Evolution Model but it does not offer any support for design management what limits its practical use. He prioritises the Spiral Model [21] as an appropriate process model which should be developed further [50].

Criticism of current systematical approaches to design

Maffin [46] states, that a barrier for the application of design methodologies is their focus on original design, which is the most challenging. However, design practice needs support for the more frequent task of adaptive design. Because most design projects are not original design, the use of design methodologies is very limited. He criticises existing design methodologies because of their focus on an improvement of product quality by exclusion of important context factors such as available resources, management conditions etc. Maffin suggests that new models of the design process should support context-dependent interpretation instead of being pure prescription of an idealistic process.

Macmillan et al. [51, 52] compared process models from architecture and engineering design with the goal to develop a generic process map for the conceptual phase of building design. Based on this comparison they criticise the following aspects of existing models:

- most models describe a sequence of stages which, typically, imply iteration within but not between stages
- most models suggest starting with an analysis of requirements prior to the generation of possible solutions – none starts by taking an existing concept and modifying it to suit new needs
- most models propose what should be undertaken, but not why it should be performed
- most models do not indicate whether a tasks has to be performed individually by different team members or in collaboration
- most models focus on the problem requirements and their solution, by neglecting social aspects such as staffing and communication

Much of their criticism focuses on an insufficient support of activities belonging to design management rather than product design. They suggest that both aspects need to be considered in order provide useful support to a design team.

Wynn and Clarkson [33] criticise that procedural approaches (design methodologies) include many methods for the early stages of design by nearly excluding the embodiment and detail design phase. Even though, these phases have a much longer duration. They state that many authors believe that the creative leap between problem statement and solution concept is the most challenging problem in design. Although highlighting the importance of the creative leap none of the approaches prescribes the creative leap itself. Models highlighting the importance of the early phases are often of limited use in practice because most real design projects have constraints such as exiting products or legislative requirements [33].
The product-focused perspective of many procedural approaches limits their use because it excludes management aspects which are of major importance for designers [33].

Further criticism of current design methodologies are that despite often mentioned transdisciplinary collaboration is not explicitly supported by current approaches [43].

Sadek [30] analysed design methodologies from mechanical engineering, mechatronics, systems engineering and service engineering. He criticizes that current approaches from service design, which are mainly based on approaches from mechanical engineering (e.g. VDI 2221 [13]) and software engineering, offer only few specific methods especially for the conceptual design phase.

Some aspects which are not fully considered in procedural (idealistic) models of the design process are such as: goal iteration which is a constant part of real design processes, and designers seldom explore alternatives which are not on the way to a solution [50].
Brooks [50] states that designers do not work according to idealistic models, especially experienced designers. Therefore, he argues that idealistic models such as the Waterfall Model [1] are inappropriate models of the design process and should not be used any longer.
Brooks [50] is worried whether these models are taught to students in such a way that these are perceived as idealistic models which do not represent real processes, and as a consequence of such trainings applied poorly in practice.

5. CONSOLIDATION OF FINDINGS AND GUIDANCE FOR FURTHER DEVELOPMENT OF DESIGN METHODOLOGIES

Similarities across disciplines

The reviewed comparisons show some similar findings. Most authors state that despite the considered disciplines are different; procedural approaches have similarities across disciplines:

- They have a generic core of stages [1, 25, 42, 45, 44, 47, 51, 52], even though not all models cover the same span of the product life cycle. Typical stages which can be found are [47]: *Establishing a need, analysis of task, conceptual design, embodiment design, detailed design, implementation phase*
- They propose a stepwise, iterative process [1, 33, 51, 52].

However, these similarities are rather abstract [25].

Approaches from mechatronics and service design show many similarities to other disciplines because the underlying process models are basically adaptations of models from disciplines such as mechanical engineering and software design, but they do not provide the same wide range of methods [30, 43].

Differences between disciplines

Lawson [34] argues that similarities between design process models do not prove that designers work similar in different disciplines, as the process models usually propose a sequence of intermediate results but not how to create these. Therefore, more detailed comparisons are necessary.

Especially approaches from mechanical engineering and architecture show differences when looked at on a detailed level [38], for example (see Table 1): differing perceptions of problem structures (tree-like vs. lattice-like), differing process representations (linear vs. spiral), and differing starting points of the design processes (problem-analysis vs. solution-conjecture).

Possible explanations for differences between approaches are not exclusively differences between the disciplines but also differing characteristics of the products being developed [25].

Found conclusions

Independently from the analysed disciplines different authors [34, 40, 50] conclude that design is not a rational and sequential process as most idealistic models suggest. Furthermore, two slightly different conclusions can be found in literature:

- Process models are no correct representations of reality; they need interpretation [33, 36, 40, 50].
- A generic applicable approach does not exist - process models need (context dependent) adaptation [34, 42, 46].

The first conclusion treats procedural approaches as guidelines – as heuristic methods which need interpretation. If designers are familiar with such guidelines and use them at least as mind-sets design work will benefit because of a shared vocabulary and understanding of dependencies within the process.

The second conclusion treats procedural approaches in a more rigorous way. The process models are seen as prescriptions for design work, and as a basis for planning and design management. This perspective represents what design methodologies could be if developed further accordingly.

Guidance for further development

Starting points for further development of procedural approaches are provided by the criticism of current approaches found in the consulted literature. Important aspects are:

- Current approaches focus on original design, despite the majority of design tasks are based on existing designs [33, 46].
- Current approaches focus on development projects initiated by market pull. Technology push as an alternative impulse for product development is not appropriately considered [47].
- Current approaches focus usually either on design or on management. Both aspects have to be considered in order to provide an improved support [51, 52].
- Current approaches do not explain how to perform design activities (only what to do) [34, 40].
- Current approaches do not explain the rationale of the proposed processes [51].
- The creative process is not sufficiently represented in current approaches [33].

- Transdisciplinary team-work is not sufficiently supported by current approaches [43].
- Goal iteration is not sufficiently considered in current approaches [50].
- A pattern found in different disciplines is that knowledge about problem and solution emerges together (Co-Evolution) [34, 40, 48, 49]. So far this is not appropriately represented in current approaches [50].

Two suggestions for further development are explicitly provided. Blessing [1] proposes to merge product (solution) and problem-oriented approaches. Macmillan et al. [51, 52] propose to merge the project-oriented approaches with design-oriented approaches.

6. DISCUSSION

The literature study shows that many authors share the believe, that procedural approaches are suitable means in order to offer support for designers in different disciplines, even though current approaches need further development as different aspects of designing are not sufficiently considered. The authors differ in that way that there is no consensus how detailed such a support should be and how detailed it can be. But consensus exists that further development of procedural approaches and further research is required.

The literature consulted in this review and thus the findings of this paper have some limitations which may serve as guidance for further research on this topic.

It is important to consider, that the found similarities between process models for example that most approaches contain a conceptual design phase do not necessarily mean that the content of what is called a concept is similar in different disciplines. But a similar meaning is important for linking or integrating approaches from different disciplines in order to support transdisciplinary collaboration. Therefore, this needs to be verified. A possible way to do this is to compare design models, i.e. representations of intermediate results of the design process. A framework for such an analysis is described in [53].

Most of the found comparisons focused on mechanical engineering and architecture. Only few examples which are mainly from a younger date include other disciplines such as fashion design, service design, software design and mechatronics. Further procedural approaches especially those from a younger date, which were not considered in the consulted literature, should be analysed in order to complement the results of the existing comparisons.

Transdisciplinarity and collaboration between different disciplines, are discussed only recently in the literature covered by this review, as this is only addressed in approaches from mechatronics and for the development of product service systems which were analysed only by few authors.

7. CONCLUSIONS

The decision on which level of detail design processes should be described is a balancing act. The consequence of an abstract model is that the model covers a wide range of different contexts but it is of limited use because it offers no context-specific support. The consequence of a detailed model considering a specific context is that only a specific group of designers will be able to use it for a specific purpose.

In consequence many different approaches have been proposed in the past. The differences are due to different focuses of the authors e.g. design or project-focussed approaches. Differences can also be found between product-focussed and problem-focussed approaches.

The extent to which design approaches appear similar across disciplines depends on the perspective of the analysis. The similarities reported in the literature covered by this review were found on an abstract level – on the level of design stages. The identification, analysis and explanation of differences between procedural approaches seem to be more difficult.

Based on the reported findings it is expected that more detailed analyses which include the comparison of the activities proposed in procedural approaches may offer the chance to identify important differences. In order to contribute to an improvement of existing approaches such an analysis has to be complemented by an analysis of the context the particular approach was proposed for. Tracking back of differences in procedural approaches (including the activities) to different contexts may serve as a basis for recommendations for the adaption of other approaches respectively the adaptation of a consensus model.

A consensus model which may serve as a basis for a transdisciplinary approach would have to merge problem- and product-focussed approaches and more importantly design- and project-focussed approaches. In order to be applicable such an approach must be adaptable to different contexts and different design tasks (not focussing only on original design and market pull).
It seems promising to combine the vertical dimension (linear, procedural) and the horizontal (iterative, problem-solving) of Hall's morphology of the systems engineering process as proposed by Roozenburg and Cross [40] in order to merge different approaches which have been proposed for different contexts. Considering both dimensions would also enable more detailed analyses of existing procedural approaches and the analysis of context dependencies as described earlier.
Even though this review takes a process focussed perspective it is clear that design cannot be explained solely by process models. Much work needs to be done involving other perspectives for example focussing on discipline specific cultures (education), communication (terminology, design models), and management styles.

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