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AN ANALYSIS OF DESIGN PROCESS MODELS ACROSS DISCIPLINES

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1. Motivation

Many design problems show a rising complexity and they often do not match the boundaries of a single discipline. As a consequence, designers from different disciplines have to collaborate.

Design research aims at supporting practitioners by providing methodologies, methods, tools and recommendations but much of the developed support is rather mono-disciplinary.

[Birkhofer 2011a] reviewed contributions of several experts in the area of design methodology and one of his conclusions is: "Overall, the propositions indicate that classic Design Methodology has deficits in supporting current or even future development work that necessitate a substantial reformation." [Birkhofer 2011a, p. 217]

As reformation does not mean to start from scratch, it can build upon existing work. As much of the existing work is fragmented or related to a (discipline-) specific context, consolidation is required.

A challenge for consolidation and also for overcoming the boundaries of current rather mono-disciplinary approaches is 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.

A comparison of approaches in different disciplines and a rethinking of concepts are necessary.

The research presented here is based on a comprehensive literature study incorporating design methodologies and process models from nine disciplines and was guided by the overall research question: What are commonalities and what are differences of design process models across disciplines?

2. Existing comparisons of design process models

Some authors conducted comparisons of design methodologies and design process models, thus contributed to a consolidation. [Howard et al. 2008] analysed 23 process models (see Figure 1) mainly from mechanical engineering. They identified the following set of typical design stages: *establishing a need, analysis of task, conceptual design, embodiment design, detailed design, and implementation*.

Other authors e.g. [Roth 1982] (mechanical engineering – german schools), [Ogot 2004] (mechanical engineering), [Kim and Meiren 2010] (service design), and [Möhringer 2004] (mechatronics) identified similar sets of common design stages.

An overview and consolidation of existing comparisons of design methodologies and process models is provided in [Gericke and Blessing 2011]. Based on the analysis of the existing comparisons it was concluded that design processes have similarities across disciplines: they have a core of common design stages; they propose a stepwise, iterative process.

The reviewed literature also provided several critiques of current design methodologies and process models:

- Current approaches focus on original design, despite the majority of design tasks are based on existing designs.
- Current approaches focus on development projects initiated by market pull. Technology push as an alternative impulse for product development is not appropriately considered.
- Current approaches focus usually either on design or on management. Both aspects have to be considered in order to provide an improved support.
- Current approaches do not explain how to perform design activities (only what to do.
- Current approaches do not explain the rationale of the proposed processes.
- The creative process is not sufficiently represented in current approaches.
- Transdisciplinary team-work is not sufficiently supported by current approaches.
  Goal iteration is not sufficiently considered in current approaches.
- A pattern found in different disciplines is that knowledge about problem and solution emerges together (Co-Evolution). So far this is not appropriately represented in current approaches.

[Blessing 1996] and [Macmillan 2002] provide concrete suggestions for further development. Blessing proposes to merge product (solution) and problem-oriented approaches. Macmillan et al. propose to merge project-oriented approaches with design-oriented approaches.

A limitation of the comparisons reviewed in [Gericke and Blessing 2011] is that most of the comparisons focus on mechanical engineering and architecture. Only few or individual approaches from other design disciplines such as service design, software design, and mechatronics are considered. A further limitation of the reviewed comparisons is that only few recent approaches are considered.

Models	Establishing a need phase	Analysis of task phase	Conceptual design phase	Embodiment design phase	Detailed design phase	Implementation phase
Booz et al. (1967)	X	New product strategy development	Idea generation / Screening & evaluation	Business analysis / Development	Testing	Commercialisation
Archer (1968)	X	Programming / data collection	Analysis / Synthesis	Development	Communication	X
Svensson (1974)	Need	X	Concepts	Verification / Decisions	X	Manufacture
Wilson (1980)	Societal need	Recognize & formalize / FR's & constraints	Ideate and create	Analyze and/or test	Product, prototype, process	X
Urban and Hauser (1980)	Opportunity identification	Design		Testing		Introduction (launch) / Life cycle management
VDI-2222 (1982)	X	Planning	Conceptual design	Embodiment design	Detail design	X
Hubka and Eder (1982)	X	X	Conceptual design	Lay-out design	Detail design	X
Crawford (1984)	X	Strategic planning	Concept generation	Pre-technical evaluation	Technical development	Commercialisation
Pahl and Beitz (1984)	Task	Clarification of task	Conceptual design	Embodiment design	Detailed design	X
French (1985)	Need	Analysis of problem	Conceptual design	Embodiment of schemes	Detailing	X
Ray (1985)	Recognise problem	Exploration of problem / Define problem	Search for alternative proposals	Predict outcome / Test for feasible alternatives	Judge feasible alternatives / Specify solution	Implement
Cooper (1986)	Ideation	Preliminary investigation	Detailed investigation	Development / Testing & Validation	X	Full production & market launch
Andreasen and Hein (1987)	Recognition of need	Investigation of need	Product principle	Product design	Production preparation	Execution
Pugh (1991)	Market	Specification	Concept design		Detail design	Manufacture / Sell
Hales (1993)	Idea, need, proposal, brief	Task clarification	Conceptual design	Embodiment design	Detail design	X
Baxter (1995)	Assess innovation opportunity	Possible products	Possible concepts	Possible embodiments	Possible details	New product
Ulrich and Eppinger (1995)	X	Strategic planning	Concept development	System-level design	Detail design	Testing & refinement / Production ramp-up
Ullman (1997)	Identify needs / Plan for the design process	Develop engineering specifications	Develop concept	Develop product		X
BS7000 (1997)	Concept	Feasibility	Implementation (or realisation)			Termination
Black (1999)	Brief/concept	Review of 'state of the art'	Synthesis / Inspiration	Experimentation / Analysis / reflect	Synthesis / Decisions to constraints	Output / X
Cross (2000)	X	Exploration	Generation	Evaluation	Communication	X
Design Council (2006)	Discover	Define	Develop		Deliver	X
Industrial Innovation Process 2006	Mission statement	Market research	Ideas phase	Concept phase	Feasibility Phase	Pre production

Figure 1. Typical stages of process models from mechanical engineering [Howard et al. 2008]

Therefore, one of the research questions addressed in this paper is whether process models from other disciplines and more recent models differ from the picture drawn by existing comparisons.

3. Literature study

3.1 Study design

The literature study presented in this paper started with a collection of existing process models. In order to cover models which are established in the research community, an analysis of existing comparisons was conducted.
The resulting list of models was extended with further known models and by an extensive literature study. Thus, 124 process models from 9 disciplines were collected in total (see Figure 2). The considered disciplines are: *mechanical engineering, industrial design, systems engineering, architecture/building design, software design, service engineering, mechatronics, product-service-systems (PSS)-design* and models which claim to be applicable independent from a specific discipline (*transdisciplinary approaches*). Despite a lot of effort was put into the collection of a representative set of process models, this list does not claim to be exhaustive.
These models were analysed in two rounds. In the first round 82 models were categorised in order to get an overview. 42 models were excluded from the first round because the original literature did not provide sufficient information for a categorisation, or because the original text was not accessible.
The second round was intended to compare and analyse the design stages described by these process models. 64 stage-based models (or models which combine a stage-based and an activity-based perspective) were analysed in the second round.

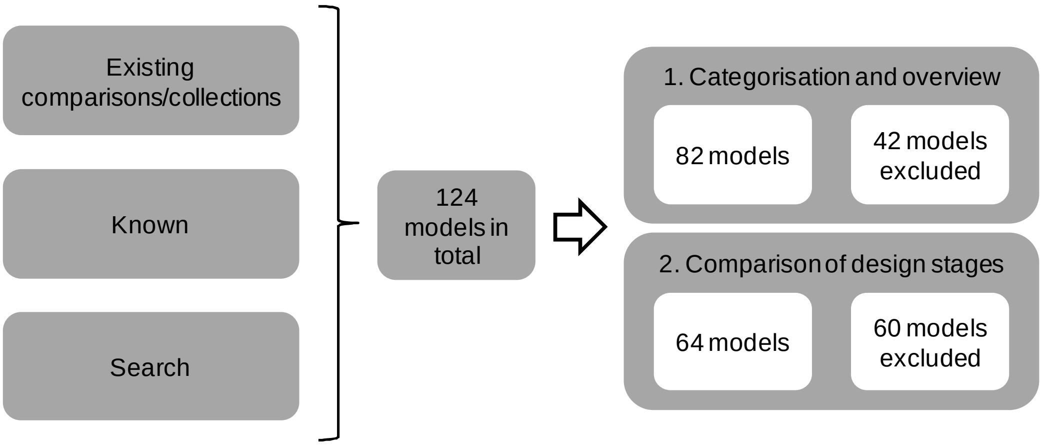

Figure 2. Selection of analysed models

3.2 Findings

3.2.1 Categorisation and overview

Out of the group of 124 models, 82 were selected for the first analysis. The analysis is focused on:

- the <u>age</u> of the models,
- the <u>type of support</u> they offer (design process model, methods intended as a support of the design activities, and methods which support the management of a design project),
- a <u>categorisation</u> regarding different aspects (whether the models are stage-based or activity-based, solution-oriented or problem-oriented, and whether they are design-focused or project-focused),
- the <u>form</u> of the graphic representation of the models.

The categorisation is based on schemes described by Blessing [Blessing 1996] and [Wynn and Clarkson 2005]. Blessing distinguishes between stage-based models, activity-based models and combined models. She further distinguishes models which are solution-oriented and problem-oriented. Wynn and Clarkson extend Blessing's scheme by characterising process models as abstract, procedural, or analytical (the category of analytical models is not relevant in this analysis), and further as design-focused or project-focused. Short descriptions of these categories are given in Table 1.

Table 1. Categorisation scheme

Category	Description
process model	a representation of the design/product development/product creation process
design methods	methods intended as a support of the design activities (e.g. functional models, design FMEA)
management methods	methods which support the management of a design project (e.g. project planning techniques)
stage-based models	„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.“ [Blessing 1996]
activity-based models	„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.“ [Blessing 1996]
combined	Models which represent the design process by a combination of a stage-based and a activity-based description.
solution-oriented models	emphasise the analysis of the product idea [Blessing 1996]: problem ➔ concept ➔ product
problem-oriented models	emphasise the analysis of the addressed problem; after an initial proposal for a solution the solution respectively the requirements list is abstracted, before other solutions are explored [Blessing 1996]: problem ➔ abstraction ➔ concept ➔ product
design focused models	emphasise product design activities, e.g. improvement of the products functionality and performance [Wynn and Clarkson 2005]
project focused models	emphasise design management activities, e.g. analysing the context of the design process and includes cost-related activities (product planning, marketing, risk management) [Wynn and Clarkson 2005]
abstract models	represent the design process at a high level of abstraction [Wynn and Clarkson 2005]
procedural models	represent the design process on a more detailed level of abstraction highlighting specific aspects of a design process [Wynn and Clarkson 2005]

Results

Age

The average age of the analysed process models is 24 years. The models proposed for mechanical engineering, industrial design, systems engineering, and building design/architecture are in average 32 years old (the average is for each discipline similar). Considering that most of the models are based on or influenced by other already established (thus older) models, the roots of these models can often be traced back to initial models from the 1960's and older ones.

The models proposed for the other disciplines are much younger; their average age is 12 years. Even though, many of these models are inspired by models from the other disciplines, leading to many similarities of the models themselves but also giving them a much longer history.

Type of support

The analysed literature can be divided into design methodologies, which contain a process model in combination with methods which support specific activities during the process, and literature which focuses on the design process or specific aspects thereof. The models proposed in design methodologies are usually more detailed.

Methods are more often proposed in the design-focused literature compared with the project-focused literature (see Table 2). Only few authors propose design methods and management methods and try to combine a design-focused and a project-focused perspective on the design process.

Table 2. Categorisation and overview of analysed process models

		type of support			process model category: stage-based - activity based				solution oriented - problem oriented				design-focused - project-focused				form			
	number of analysed models	process model	design methods	management methods	stage-based	activity-based	combined	not clear	solution-oriented	problem-oriented	not applicable	not clear	design-focused	project-focused	combined	not clear	Sequential/Waterfall	Spiral	V	other
total	82	82	38	17	50	14	18	1	23	48	3	7	47	28	3	0	62	6	4	9
mechanical engineering	39	39	28	8	26	6	7	0	13	22	1	2	30	6	2	0	33	3	0	3
industrial design	1	1	1	0	1	0	0	0	0	1	0	0	1	0	0	0	1	0	0	0
systems engineering	5	5	1	4	0	0	5	0	0	4	0	1	0	5	0	0	3	1	0	1
building design (architecture/civil engineering)	10	10	3	2	3	6	1	1	6	2	1	1	7	3	0	0	8	0	0	2
software design	5	5	2	1	4	0	1	0	1	4	0	0	1	2	1	0	1	1	1	1
service engineering	8	8	0	1	8	0	0	0	1	4	0	3	2	6	0	0	7	0	0	1
mechatronics	6	6	0	0	3	0	3	0	2	4	0	0	3	3	0	0	2	1	2	1
product service systems	5	5	1	1	5	0	0	0	0	4	1	0	0	3	0	0	4	0	1	0
transdisciplinary approaches	3	3	2	0	0	2	1	0	0	3	0	0	3	0	0	0	3	0	0	0

Process model category

All of the models are rather abstract representations of the design process. The distinction of [Wynn and Clarkson 2005] between abstract and procedural approaches was difficult to apply. According to Wynn and Clarkson abstract approaches are representations of the design process at a high level of abstraction and procedural approaches are more detailed representations highlighting specific aspects of a design process.

Some models which are abstract graphic representations are supported by explicatory text and methods, what qualifies them as procedural. Many of the stage-based models represent information which qualifies them as procedural but the amount of information is too limited or the detailing is only provided for specific stages. This blurs the border between abstract and procedural and makes a distinction to some extent arbitrary. Therefore, this categorisation was not used in this analysis.

Most of the analysed models can be best described as stage based. More detailed models usually combine a stage-based and an activity based representation (see Table 2). The activity-based models are typically adaptations of a basic problem-solving process.

The majority of the analysed process models represent a problem-oriented design approach. Almost all of the models proposed in the last two decades represent a problem-oriented approach.

Form

The majority of the models represent the sequence of stages which form the design process in a rather simple way, often referred to as sequential models, linear or waterfall models in the literature (see Table 2). Only few models have spiral or a V-form.

Spiral models highlight that in each of the subsequent stages a recurring sequence of similar activities has to be performed. The V-shaped models highlight the need for decomposition of the design problem during the initial design stages and the stepwise integration of the developed solutions and their evaluation during the later stages.

Some models do not fit into these categories. They represent the design process e.g. as a circular process or as a network of activities without a fixed sequence.

Nearly all of the process models, even those which represent the design process as a sequence refer to the design process as an iterative one – some highlight the iterations more intensively (for example in software design and human centred design (transdisciplinary) approaches) others do not indicate this in the model, but the authors address this characteristic in the text.

3.2.2 Comparison of design stages

The second part of the analysis of the process models focuses on the coverage of the process models, i.e. what part of the product life cycle is addressed in these process models. Due to this focus only stage-based and combined models were analysed.

This comparison is based on results of existing comparisons of process models from mechanical engineering by [Roth 1982], [Howard et al. 2008], [Ogot 2004], and a comparison focussing on service design process models by [Kim and Meiren 2010]. These comparisons are supplemented by an analysis of further process models out of the same disciplines and models from other disciplines.

After a first screening of the models it became clear, that the terminology which is used in the models is quite similar. In order to assure the comparability of the process models, i.e. that a similar wording refers to similar content of a stage, an extensive analysis of design models which are proposed in different disciplines was conducted [Eisenbart et al. 2011]. Based on this additional literature study, it was concluded that similar design states (information about the design) exist across different disciplines, thus at least on the abstract level of design stages the process models are comparable.

Results

The coverage of the individual process models is shown in Figure 3. Grey areas indicate that a process stage, which is listed on top of the figure, is covered by a model. The naming of the design stages used in this comparison is based on the comparison of [Howard et al. 2008] and was extended by a *use* and a *closeout* stage. A short explanation of the wording is provided in Table 3.

The main findings from the analysis of the life-cycle coverage of the process models are listed in the following:

- Most of the models cover the core stages (*analysis of, conceptual design, embodiment design,* and *detailed design*).
- The *establishing a need* stage is emphasized in models from service design, PSS-design, software design, systems engineering, and many of the more recent models from mechanical engineering. In many of the other models the importance of the user need and the design problem is mentioned but not described as integral part of the design process.
- The *implementation* stage is emphasised in systems engineering, building design, software design, service design, mechatronics, and PSS design. Models from mechanical engineering and building design/architecture highlight in this stage the production or realisation. Models from system engineering, software design, mechatronics, and PSS-design focus on integration, test, and validation.
- The *use* stage is covered in most of the systems engineering models and in individual models from building design/architecture, software design, service design, and PSS-design. In software design the focus during the use stage is on maintenance of the product, in the other disciplines the focus is on review and monitoring in order to gather feedback about the product.
- The *closeout* stage is only covered by approaches from systems engineering. As the systems addressed by these approaches are usually complex and require often a considerable infrastructure the closeout turns into an individual stage which also requires management and engineering activities.

Although, the coverage of the product-life-cycle is often similar in the different process models, an analysis of the explaining text and a review of the offered methods show that they emphasise the stages differently. The design-focussed literature focuses mainly on the *conceptual, embodiment,* and *detailed design* stages (i.e. explain typical challenges in a stage and provide support). Human centred approaches focus on the *establishing a need* and con*ceptual design* stages (the focus can vary dependent on the product under development [Gericke and Maier 2011]). Project-focused approaches often cover the process from *establishing a need* until *implementation* or beyond.

An important difference between the processes from the different disciplines is the duration of each of the stages. In a systems engineering context (large scale systems such as airplanes and spaceflight equipment) the *conceptual design* stage may take several years, while in other disciplines this stage takes only months or weeks. A similar situation can be found when comparing the *implementation* stage, for example in building design/architecture and software design.

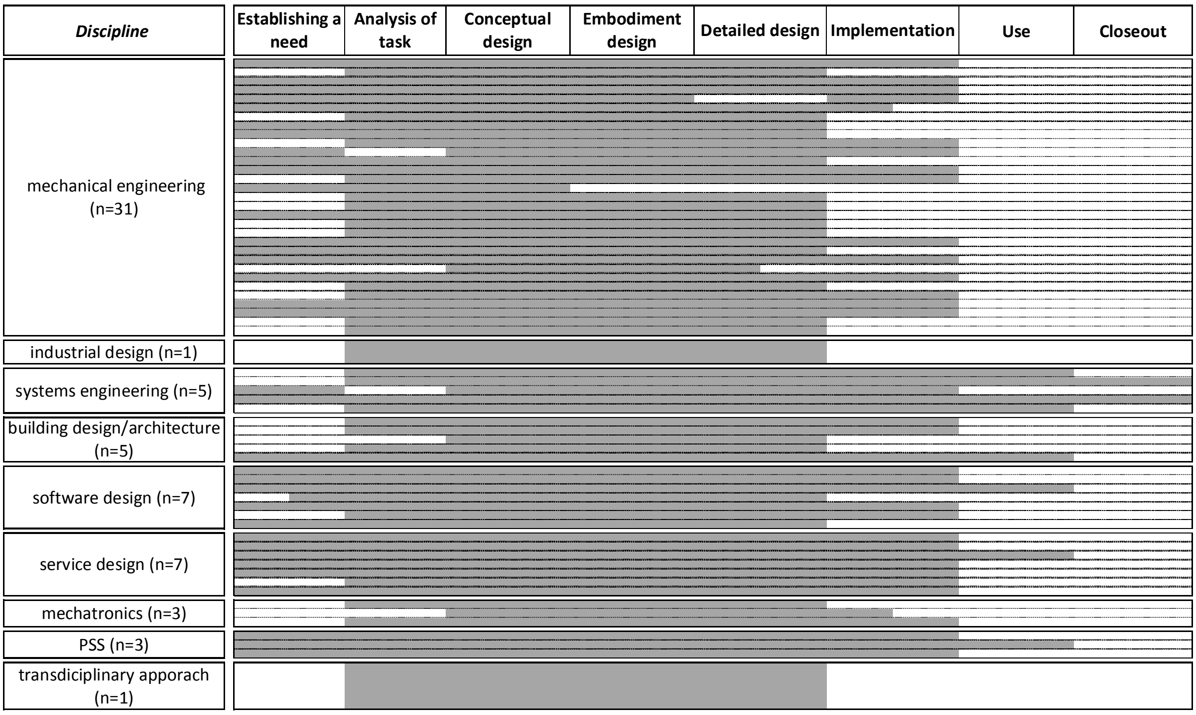

Figure 3. Comparison of design process models

Table 3. Description of the design stages

title	description
1. Establishing a need	initiation of the design process by a product idea, or the identification of a need or a problem
2. Analysis of task	detailed analysis of the initial description of the task/need/product idea; additional information are gathered
3. Conceptual design	development of abstract/principle solutions (concepts) which solve the problem
4. Embodiment design	detailing of the conceptual solution
5. Detailed design	integration of sub-solutions, refinement and finalisation of the solution
6. Implementation	integration, manufacturing, installation, test, approval, launch of the product
7. Use	operation, monitoring, maintenance of the product
8. Closeout	recycling, disposal, update/evolution of the product

3.2.3 General findings

Most authors try to describe the design process branch-independent (i.e. to offer a support which can be applied on a wide range of products which belong to a specific discipline). But the methods they propose, the challenges they address, and the examples they give often imply that they have a context in mind, which they usually do not explain.

As reported in the comparisons of process models by [Wynn and Clarkson 2005] and [Maffin 1998] the analysed process models focus mainly on original design. Only few authors propose modifications of the original design process for adaptive or variant design. These modifications usually mean a simplification or deletion of the early stages of the design process or parts thereof. Exceptions can be found in software design.

A further interesting finding is that the interaction of different processes which contribute to the creation of the final product is usually not explicitly addressed in the analysed process models. The design process is usually represented as an isolated process and only some of the authors address the interaction of the design process with other relevant business processes.

3.3 Limitations

Comparing design process models proposed in literature has some limitations. The level of detail of the information provided by the authors limits the level of detail of the comparison. Unfortunately literature which provides less detailed information sets the limit for an analysis.

Many of the process models are purely stage-based descriptions of the design process and often only little explanation is provided. Therefore, this study is seen as an initial study which will be followed by further studies focussing on more detailed models, thus being able to analyse them in more detail.

A further limitation of this comparison is that many information regarding assumptions of the authors about the design context are not available. The high level of abstraction and the lack of context information are the main limitations of the comparison.

4. Discussion

4.1 Unequal evolution of design practice and design methodology

The development of the analysed design process models has a long history. Many of the models build on concepts developed in the 1960' or 70's, that means most of the current models are the result of an evolutionary process.

The evolutionary development of the approaches, which can be traced back to similar roots, lead to process models which are now adapted to specific design disciplines but still have many similarities. Recent process models are usually stage-based or combine a stage-based and an activity based perspective (thus, being more detailed) and propose a problem-oriented approach to design.

Most of the models are very abstract representations of the design process. The high level of abstraction is due to the goal of the authors to propose branch-independent support, which is applicable to a wide range of products and design problems within a discipline.

Changes in design practice during the last decades such as the development of computer-aided tools and products which require more and more intensive collaboration between different engineering disciplines have affected design practice considerably [Birkhofer 2011b].

The established approaches have not been adapted to many of these changes to date, what supports [Birkhofer's 2011a] conclusion that a "substantial reformation" is necessary.

4.2 Isolated views are dominant in the literature

Based on a literature review Maier and Störrle [Maier and Störrle 2011] identified different characteristics of engineering design processes. They state: "Engineering design processes are embedded in an ecosystem of processes with multiple interdependencies and interactions between." One of the related characteristics is that process-process interactions occur.

In contrast to that most of the analysed process models show the design process as an isolated process (i.e. they provide no references to other disciplines or processes of other business functions than engineering), only few models show parallel activities of different stakeholders in order to highlight that design is not executed as an isolated process.

4.3 Challenges for merging different perspectives

Some authors propose approaches which incorporate a process model, design methods and management methods and try to combine a design-focused and a project-focused perspective on the design process but they focus on only one discipline. Approaches which try to incorporate different disciplines are usually restricted to a management perspective.

A possible explanation is given in the following. The design-management (project)-focused approaches show much more similarities across disciplines than design or engineering-focused approaches because they are often based on more abstract process models compared with the design-focused approaches and propose similar or even the same management methods. The design-oriented

approaches (even similar on an abstract level) show differences on a more detailed level (if provided). Although, the proposed design methods and design models have similar purposes, the terminology and the design models are different.
A further challenge which needs to be addressed in order to couple different disciplines is that the disciplines emphasise the design stages differently and interpret the beginning and the end of the process differently.
Starting from a design management perspective seems promising in order to merge project and design-focussed approaches from the same discipline but incorporating different disciplines requires also the development of new support.

5. Conclusions

Product development is not an isolated and mono-disciplinary process as represented by many of the models proposed in literature. Real design processes are often executed as an interdisciplinary endeavour. They are affected by and interact with other business processes within a company. Each group of people which belongs to a specific design discipline or business function has its own perspective on the process. None of them is more important than the other as product development requires all of these people.
A reformation of design methodology should incorporate all of these different perspectives and provide a consistent framework to the people involved in product development, thus supporting the development of a shared understanding of the whole process. A further aspect which needs to be considered is the required extended coverage of the product-life-cycle in disciplines such as software design, service design, and product-service-system design which differs from classical approaches from mechanical engineering, which often end when the design is completely described and manufacturing starts.
A consensus model of the existing discipline-specific models seems not to be sufficient in order to support interdisciplinary design, because the level of abstraction that is necessary to be discipline-independent is much too high for an effective support. But starting with such a bird-eye view enables a coupling of the different discipline-specific approaches.
A reformation needs more than comparing existing process models. As design research aims to provide support to practitioners a major concern should be to analyse the needs of “our customers”, that means: Who are our customers? What are their functions and responsibilities in the process? Do we have to address designers, design managers, either groups, or even additional groups? Clarifying this is important as the perspective on the design process and the needs will probably be different for different groups. And with respect to a reformation of design methodology, a further question should be: What are the users’ requirements regarding such a support?

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