Herbert Birkhofer *Editor*

The Future of Design Methodology

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Foreword

I am very pleased to be invited to write a few words of introduction to this book of papers written for the Colloquium held in honour of Professor Herbert Birkhofer on the occasion of his retirement after a long and distinguished career. For the past two decades Professor Birkhofer has been part of a great movement in design research in a worldwide community that he has been especially instrumental in nurturing and developing. This book, which draws together leading experts in design methodology, both reflects the great progress that has been made by this community and identifies the challenges for the future development of the topic.

The book is introduced by Professor Birkhofer, highlighting the motivation and objectives and explaining the structuring of the 21 contributions into three sections. Each section comprises a number of chapters written by invited authors and with a summary by Professor Birkhofer. A conclusion addresses promising working areas for future design research. The breadth of discussion and expertise of the authors mean that the book should be essential reading for design researchers at all levels and in all disciplines!

Taken as a whole, the chapters of this book demonstrate the diversity and the achievements of research in design methodology, but also very ably illustrate the challenges that the research community faces in its future development. As such, the Colloquium is very timely, in that it has drawn out a number of very valuable suggestions on the directions the community might take, especially in working together to organise and consolidate what has been learned and to identify the research agenda for the future. In this respect I believe that the Design Society, which Professor Birkhofer so ably guided through its formative years as its first President, has a key role to play.

Chris McMahon, President, Design Society

Preface and Acknowledgements

This book developed from a reflection on the current state of Design Methodology. It aims to determine the strengths and weaknesses, finding solutions to overcome these weaknesses while maintaining the strengths. This goal can only be reached if the various viewpoints, assessments and perspectives of the international community are considered. These prerequisites are met by the fact that almost all authors are DESIGN SOCIETY members. The institution, as an international community, embraced product development and supported its further development, with many projects in the areas of research, application, education and training.

This book does not aim to determine which course is to be taken to further expand design methodology to meet the rapidly changing needs of design practice in industry and provide findings for teaching. Rather, this book is a collection of reflections, ideas, approaches and propositions for optimisation, additions or alternatives. Every author is passionate about formulating better approaches, strategies and methods to support development work. There will be the denomination of possible spheres of activity and the formulation of solution propositions, rather than *The Future of Design Methodology* being prophesied. If the book initiates discussion about the further development of design methodology within the DESIGN SOCIETY, as well as in other communities, it will have achieved its goal.

Thanks to all of the authors for their willingness to explore the future of design methodology, which they demonstrated with substantial contributions. Accepting the various obligations proves their engagement with the cause and their willingness to provide support. Special thanks go to Mogens Myrup Andreasen and Ken Wallace, who critically reviewed contributions and helped with valuable suggestions.

Special gratitude must be expressed to Shulin Zhao and Benjamin Röder at TU Darmstadt for their dedicated commitment to the editorial work and thoughtful assistance with this project. Thanks also go to Nils Lommatzsch for the English revision of this book. Additionally, Julian Sarnes performed meticulous formatting. Finally, thanks to my department, Product Development and Machine Elements (pmd) at TU Darmstadt, and employees for their willing and professional assistance on very short notice.

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Darmstadt, December 2010 Prof. Dr. h.c. Dr.-Ing. Herbert Birkhofer

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Chapter 2
Is Engineering Design Disappearing from Design Research?

M. M. Andreasen[1] and T. J. Howard[1]

Abstract Most systems and products need to be engineered during their design, based upon scientific insight into principles, mechanisms, materials and production possibilities, leading to reliability, durability and value for the user.

Despite the central importance and design's crucial dependency on engineering, we observe a declining focus on engineering design in design research, articulated in the composition of contributions to Design Society conferences. Engineering design relates closely to the 'materialisation' of products and systems, i.e. the embodiment and detailing. The role of clever materialisation is enormous where poor engineering will often manifest in a multitude of consequences for downstream activities.

In this article we will draw a picture of what happens in the embodiment phase of designing, try to create an overview of current understandings and sum up the challenges of proper embodiment. Embodiment design is just as intellectually challenging as conceptualisation but seems much more engineering dependant and intriguing in its complexity of dependencies and unsure reasoning about properties by the fact that often a multidisciplinary team is necessary.

This article should be seen as the fertilisation of this theory and terminology barren land, inspiring researchers to work on embodiment and detailing.

2.1 Disappearing Engineering Design?

Herbert A. Simon argues "that design is the central activity that defines engineering – or at the very least, distinguishes it from the "pure" sciences – because the role of engineering is the creation of artefacts" (Dym and Little 2000). We would add that design is much more than engineering and that it takes much more than engineering to create a successful product. But when it comes to design, the embodiment phase, is what distinguishes engineering design from any other form of designing.

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Design research is composed of at least two sources: The nature of the artefacts to be designed (and produced) and the nature of human designing. Hubka (Hubka 1973) created Theory of Technical Systems, which we see as a generalisation of engineering insight, but formulated for the goal of synthesis. His theory structures different aspects of artefacts and creates the link to engineering knowledge. Early ICED conferences in the 80'ies were open to engineering topics and especially the collection of topics we today call Design for X (DfX). A review paper on the content of ICED conferences' (Andreasen 2001) showed that Design for Manufacture had a peak occurrence in the 90'ies. In another review paper on the merits of the Design for X Symposia (Andreasen et al 2006) arranged by Professor Meerkamm over a 20 year period (1990-2009) it was concluded that the focus on Design for Manufacture and Cost was only sparsely treated. It seems that industrial focus also is weakened due to preferences for "low wage country" manufacture. A revitalisation of Design for Manufacture may come from module oriented development and manufacture, which is still in its infancy.

Another trend was observed from research presented at the summer school on engineering design research (SSEDR) and a number of PhD-examinations. We see here a tendency for students to prefer topics which are utilising information technology and which are treating information management aspects of designing; unfortunately this preference is not combined with an insight into the content of the information, the activities performed or the ability to articulate what is going on. The students' preferences may be explained by the problems of capturing, understanding and adding original thoughts to engineering design projects in a relative short study period, partly due to their asynchronous nature.

Of course many contributions are related to engineering design at our conferences; our concern is the area of design, which is unique to engineering, namely embodiment design. Therefore we will elaborate on the delimitation, identity, content and importance of embodiment in the following sections.

2.2 The Starting Point for Embodiment

The starting point of embodiment is not easily defined for several reasons which we will comment upon here.

Most concepts are only partially new concepts, thus it may be that only the subsystems or features are conceptually new and carry "the differences that matter" (Hansen and Andreasen 2003), and the rest of the concepts will be "carried over" or re-used from previous designs. This makes the starting point of embodiment diffuse.

The same aspect we find in the decomposition pattern shown in figure 2.1; at each function level (or systems level), for instance in car design, we actually find the pattern of *synthesis* repeated: Concept – Embodiment – Details, which means that we can't draw a line on the time axis telling where embodiment starts and ends. This has large implications for engineering design project management, where attempts are often made to use these phases to form management style stage gates (Howard et al. 2008). This is one possible cause of the confusion and the inconsistent interpretation of these terms. As the pattern of decomposing and composing the embodiment phase is diffuse; we need to find a demarcation line between conceptual and embodiment design. We suggest that the phases be defined by the dominant activity, where point ‘X’ in figure 2.1 marks the transition from conceptual to embodiment design. Thus embedded in the embodiment phase we find tasks of conceptualisation of lower system level organs (function carriers). Finding the real shapes and distributions of the curves would make for interesting research.

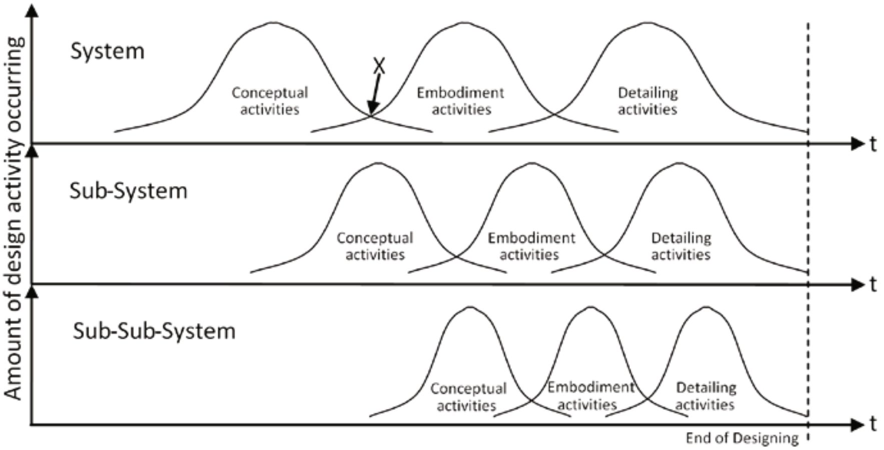

Fig. 2.1 The design activity decomposes into several levels of repeated design phases

To conclude: The starting point for embodiment is an inhomogeneous definition of the design, partially described as new concept(s), partly as carried over, embodied sub systems. Therefore the embodiment stage has to start with an overall definition of the embodiment, a structural scheme or architecture, to be filled in during the design activity.

2.3 What Happens During The Embodiment Stage?

Embodiment follows after conceptual design and is followed by detail design, claim Pahl and Beitz (Pahl and Beitz 2007), even if we often see necessity to make embodiment design work before a concept can be released. They see embodiment as composed by determination of preliminary layout and definite layout. Layout design is creating general arrangement and spatial compatibility, preliminary form design of components fitted to a production procedure and provides solutions for any auxiliary function. The definitive layout shall allow a validation of function, durability, production, assembly, operation and cost.

Ulrich & Eppinger (Ulrich and Eppinger 2004) call what follows after concept development, System-Level Design and Detail Design. The first activity contains product family considerations, creating of a so-called architecture (might be modular) of sub systems and interfaces, considerations on supply and make-buy, elaboration of assembly scheme and finally service and cost analysis.

Ullman (Ullman 2009) distinguishes between conceptual design and what he calls product design in a similar way. He says: "..the evolving product will be composed into assemblies and individual components. Each of these assemblies and components will require the same evolutionary steps as the overall product". Ullman sees product design as being composed of new design and re-design tasks.

Birkhofer and Nordmann (Birkhofer and Nordmann 2006) combine embodiment and detail design with the area of machine elements, i.e. the systematisation of basic, frequently used, low systems level solutions in mechanical products, like connections, clutches and shafts. Their approach may be seen as a 'bottom up' approach to embodiment: The better insight one has into known solutions, their mode of action and their dimensioning, the better the embodiment design will be performed.

These four textbooks unfold many characteristics of embodiment, but so to say without any articulated theory or models which can explain the transformation from concept to a structure of specified parts. In the terminology related to the Domain Theory (Andreasen 1980) the design activity is seen as the creation of three types of system structures: an activity structure related to the use of the product, an organ structure focussing upon the pattern of functions, organs and their function relations, and a part structure (parts and interfaces) created during the embodiment activity. Though this theory goes into much detail, there remain important open questions:

- Is embodiment reasoning of a different from conceptual reasoning?
- How is function determination and organ structure transferred to a structure of parts whilst explaining part interactions?
- What is created during embodiment other than layout and 'part drawings'?

The following sections will detail the most important aspects of embodiment design, namely, function reasoning (section 2.4), structuring (section 2.5), property reasoning (section 2.6) and part design (section 2.7). The intention is to consolidate the above questions, not to answer them.

2.4 Function Reasoning

A well-known design reasoning pattern has been formulated by Gero (Gero 1990) in his FBS-model (Function-Behaviour-Structure), where the reasoning from required function to the product's expected behaviour is followed by a jump to imagined, found or synthesised structures or solutions. The premise of the theory behind the FBS model is, that you are unable to determine what the function of a structure is, without first postulating a behaviour for the structure. Also, it is not possible to reason from a function to a structure without first conceiving of a behaviour to fulfil the function.

We see function reasoning as involving the identification and synthesising of the product's aim, for which, natural language is very supportive, particularly in the process of imagining, foreseeing and articulating functions. We also state that function reasoning is composed of two patterns answering substantially different questions:

1. What do we want to do with the product?
2. What do we want the product to do?

Gero's model seems to cover the second question, where 'structure' in his model relates to the product's structure (it might be organ structure or part structure). But we may also see Gero's model as being related to another structure, namely the man/machine structure or system, thus the function reasoning regards 'what we can do with the product'.

An example, inspired from Dym & Little (Dym and Little 2000): If we are to design a ladder we face the problem: What actually is a ladder? What can we do with a ladder and how does the ladder contribute? When the ladder is used the person is situated in a higher position, but the ladder is passive. How do we articulate its function? "Allow person to rise to a higher position"? And when the person stands there: "Support person"? Shall we add more functions: "Allow transport", "Foldable"? Each of these formulations creates different pictures in our mind.

Gruber (Gruber et al. 2010) claims that the design process of a car's front door contains the following stages: Forces - Topology - CAD - FEM - Part solutions - Validation and Testing. It means that he, reasoning as a supplier, sees the door's main function as "to protect passenger". You may say that the door should deliver the functions "allow embarking", "protect against weather" and "allow locking" of the car space, but we see here the effect of car safety considerations, leading to building in a safety beam and dimensioning for energy taken up by collision.

The other pattern of function reasoning relates to the product as a structure of organs, which through causality creates the functions of the product. This reasoning is composed of finding organs able to realise certain functions, and composing these organs into a structure.

An example: When considering a portable indoor elevating platform, the raising effect may be created by organs like a motor and transmission which deliver forces to a bar mechanism which holds the platform. The output effects of each organ shall correspond to the necessary input to other organs.

Function reasoning starts in conceptualisation and continues into the embodiment phase leading to the structuring of parts.

2.5 Structuring

In the conceptual phase it is decided how the design will be used and what the product shall do. The higher levels of the organ structure may also be determined, but as mentioned above this structuring is not finalised; lower level organs may appear in the embodiment and need to be composed into the organ structure.

Figure 2.2 shows a concept (a) for a milling fixture, which shall fixate four of the items shown in b. The functions and the corresponding (very principal) organs are explained in a. Some of the necessary details, which are not shown in the concept, are shown in c and new functions/organs are indicated by an asterix. The dimensional layout in d shows the part structure. Also here new functions/organs are indicated by asterix.

Determining the part structure is the dominating task in the embodiment phase. The transition from organ to part structure is a total re-arrangement, because a single organ may be realised by several parts, and a part may contribute to more organs. The part structure is not causally determined by the organ structure, but shall respect and realise this structure. In structuring the activity the designer may reuse substantial percentage of a past design, along with components, supply parts and standard parts; thus make-buy considerations are of great importance.

Today 80% of a German car is designed and produced by suppliers. We have already seen the complexity of embodiment design; imagine it split up in the transition from concept to embodiment in separate tasks and teams, responsible for sub systems' conceptualisation and embodiment, which shall show integrity and performance in the final product.

The design of modular products is a special situation where a modular ture is created and each module is a system element in both organ structure (by ing ideally seen a one function element) and part structure (by having standard terface).

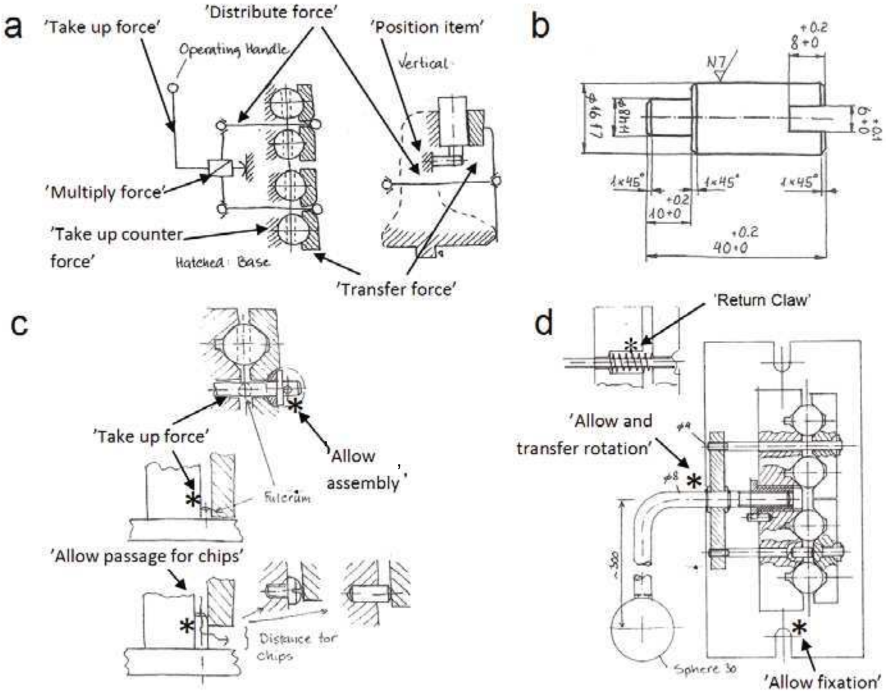

Fig. 2.2 Concept and embodiment of a milling fixture, see the text for explanation (Hubka et al. 1988)

Before CAD was introduced the normal working sequence was to elaborate on partial solutions of the concept based upon sketches and then to work out a layout, namely a scaled drawing showing the spatial arrangement of parts and their interfaces, see example in figure 2.2. Based upon the layout, the single part drawings were worked out and at the end, as a check, the assembly drawings were worked out based upon the machine drawings.

Research on the DfX-areas, mainly Design for Manufacture and Assembly, has shown the strong influence from the parts structure on the conditions and operation of the downstream activities of the product's realisation and life phases (Andreasen et al 1988, Olesen 1992). So certain structural properties are preferable to ensure alignment of the product's structure to the life phase systems and their activities. Let us mention some:

- When the product has a 'stacked structure' the assembly system can be a simple one-directional device (Andreasen et al 1988)
- It may be preferable to create the product's frame so that sub assemblies can be mounted on this frame in one layer only (it means no sub assembly is mounted on another sub assembly), benefiting both assembly and repair.

- A modular structure (US: architecture) may lead to benefits for development, supply, manufacture, distribution, maintenance, environmental effects etc. (Erixon 1988)
- A product family architecture may be utilised for enhanced alignment of the product to the manufacturing system's assets (platform thinking).
- Certain types of embodiment solutions, for instance for gear boxes, tube connections, car bodies, scaffoldings etc. appear in a limited number of variants, building modes (German: Bauweise). Choice of a certain Bauweise instead of starting with a 'neutral geometric design' may be a smart start on embodiment design (Mortensen and Andreasen 1999).

These fragmented examples belong to a higher level of complexity that concern reasoning about the embodiment of the product concerned. The reasoning is expanded to the product's life cycle phases, where the product's 'fitness for life' is determined by DfX efforts and proactive reasoning and scenario creation about what might happen in the life phases. And the reasoning is expanded to multi product development, i.e. alignment of a company's products, purchasing, facturing, distribution and sales efforts. In this higher complexity the theory of dispositions proposed by Olesen (Olesen 1992) plays an important role for plaining the dependencies between the areas.

2.6 Property Reasoning

Designing is traditionally seen to be governed by goal formulation. Beside a formulation of a team's task and the ideal business result, the goal formulation contains a list of requirements related to the ideal product solution, setting requirements for a product's properties. When a synthesised solution appears, articulated by its characteristics, the designer should be able to reason about this solution's properties and mutually compare alternative solutions to find the best solution.

Any organ has a main function and a set of solution specific properties follow this function (Hubka 1973). A simple liquid/glass thermometer may be specified to have high linearity, low zero fault, low temperature influence on its accuracy, quick response etc.; all these properties are specific for a (glass) thermometer and will govern the design process of a thermometer. Through the years, industry has collected knowledge which leads to highly delicate and precise products by understanding these function related properties. In the example in figure 2.2 we see how functions and organs have been added to the sparse set of functions shown on the concept. The main property of the fixture is "precise fixation", followed by "ease of loading/de-loading". These properties can't be evaluated from the concept sketch. Actually the property 'ease of loading/de-loading' is carried by some of the added sub functions, for instance how easy chips are removed by means of providing space for their escape and the returning the movable clutch parts by means of a spring.

Thus we are here confronted with another basic pattern of design reasoning, namely property reasoning. The pattern is well-known from the QFD method, where required properties are articulated by the 'voice of the customer' and related to the characteristics, features or properties of the product to see how well the product satisfies what the customer wants or how we can resolve complaints.

However, the QFD method proposes a very simplistic way of reasoning, as if it were evident that we can see how the product satisfies requirements or where certain properties are realised in the product. But important and complex properties, such as: reliability, utility, safety, comfort etc, in the design of a car for instance, can only be traced to the car's embodiment if we establish phenomena models of how we see these properties being realised. For the phenomenon 'car safety', the content of the phenomenon model might be the perception of collision safety ised by energy absorption, proper visual view by seat and window positions, or lock free braking obtained by ABS brakes. Thus, it is not a single model but a choice between many in order to find the best way to build in safety. Each ing of a phenomenon model and choice of means for satisfying the required erty may lead to new functions and parts, and may influence parts which have tasks not directly related to safety.

Embodiment as we see here is characterised by a difficult pattern of finalising the function reasoning and operating in the complex property reasoning pattern. Two challenges for the designer are added here. The first one is 'trade off', a very important aspect of property reasoning. This is when two or more properties are in conflict for a design and a decision must be made as to which to prioritise. It is not well understood how often designers make trade off, how they reason about it and how smart trade off may be the core of a new successful product concept.

The second challenge is the management of changes which is a time, cost and risk loaded topic in industry. Changes propagate through the part structure and need delicate adjustment, but they also disturb the property pattern often in a not easy to justify way.

2.7 Part Design

The part structure itself consists of parts in a spatial arrangement with physical interfaces. Therefore certain surfaces of the parts serve this interfacing, influencing the form, material, surface quality, dimensions and state of the parts, i.e. the characteristics of a part design as pointed out by Hubka (Hubka 1973).

The design procedure leading to a part's design has been treated by Tjalve (Tjalve 1976), who points out how to reason from the organ's characteristics to necessary part characteristics like function surfaces, interface surfaces, material fields etc. and to identify free surfaces which leave possibilities for fitting the form to a specific manufacturing technology.

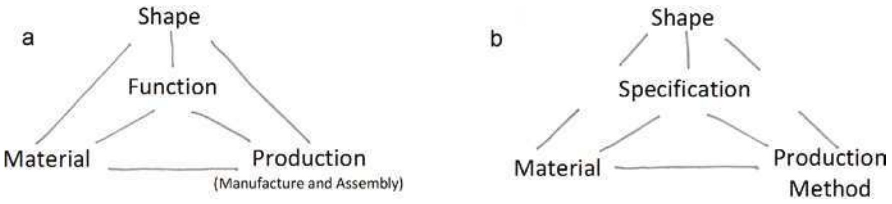

Fig. 2.3 Ullman's (a) and Jacobsen's (b) proposals for part designing (Ullman 2009, Jacobsen 1989)

Ullman (Ullman 2009) claims that "Refining from concept to product requires the consideration of four basic elements" shown in figure 2.3(a). He calls these types of reasoning for "Concurrent Design". It is interesting to compare with Jacobsen's model (Jacobsen 1989) figure 2.3(b). We believe Ullman's illustration shall be seen as rhetoric, because shape and material necessarily relate to one part, while function can't be directly related to a part. Jacobsen's illustration operates with a to 'be worked out specification' of what the part shall do, depending on the organ and the part interfaces (Jacobsen 1989).

2.8 Embodiment and Verification

When does embodiment finish? Many scholars see the detailing as the part oriented aspect of embodiment "in which a very large number of small but essential points remain to be decided" (French 1985). Other scholars focus upon the delivery of a complete set of drawings specifying the production of the product.

Can't we formulate a more strict description of an embodiment's result? In the past the finalisation of product development was traditionally the delivery of drawings. Today's insight into integration asks for overlapping design and production activities and early establishment of sales system, demanding delivery of preliminary designs and verified performance parameters for use in the sales promotion.

Verification means to ensure that you have built the thing right, asking: Does the product have the expected properties? Are we able to produce the product? These questions force companies to perform one or more verification activities based upon prototypes, pre-production and tests, which again leads to change or adjustment of the design. So it is wrong to see embodiment and engineering design as an isolated design matter. There are necessary iterations with production and the context reality which are necessary before ending the detailing.

The content of detailing seems to be an arbitrarily defined finalisation of embodiment. Of course there are tasks of creating formal production specifications but this does not really make the argument for a separate detailing phase. The proper final clarification and validation in dynamical cooperation with production, sales and distribution is much more important. To take into account these characteristics the final phase should be called ‘Implementation Design’ in line with previous research (Howard et al. 2008).

2.9 Nature of Human Design

This article is based upon several recognised theories but for the main part is a “model based theory” or theory of models based upon mental constructs which we (and maybe others?) believe will be productive in the minds of a practicing designer. We therefore derive and point out central steps of reasoning in embodiment.

In the transition from concept to part structure which was illustrated in figure 2.2 but actually as ‘post mortem’ pictures, not as explanations, we focus on a complex field of property relations, where every single required property is composed of sub properties and contributions from functions, components and parts, which may be scattered all over the product: the property field. At the same time we can focus on every single function and organ where certain function related properties shall be realised for this organ’s proper performance. But actually these considerations are speculations: How does the designer do this? It is an open question.

Do they actually skip function and conceptual reasoning by making concrete part oriented design and check the resulting properties in a trial and error approach? How do they perceive of problems and tasks? Are they much more result oriented than design methodologies’ problem orientated approaches dictate? How do they tackle the very high complexity of multiple criteria with their satisfaction spread out over a complex composed part structure?

Birkhofer (Birkhofer 2010) suggests that methodical work postulated by other researchers is considered by many developers to be “against their nature”. It means that developers create a work practise, where it is difficult to bring in new terms and structured understanding. In education the students show no negative reactions to methodology; but they are not easy to motivate for carefully performed detail design.

2.10 The Challenges in Embodiment Design

We believe that current design methodology neglects the proper nature of embodiment and that CAD systems’ abilities make it appear as if embodiment is properly supported. But one of the symptoms of the problems is the overwhelming number of design changes we see in industry. A recent study (Vianello and Ahmed-Kristensen 2010) has highlighted the extent of the design changes, stating a total of 1510 design changes were recorded over 8years of developing a Rolls Royce aeroengine, 79% of which can be traced back to systems level design and detailed design.

By consolidating and reasoning from the elaboration above, we see the following topics as central and challenging in embodiment design:

- To apply and develop engineering insight in embodiment and to keep track of the reasoning behind design decisions.
- To include long ranging influences and effects into the embodiment activity for beneficial downstream activities, especially to master structural relations between product and life phase systems.
- To master function reasoning and property reasoning and to keep track of this reasoning (designer's intent) both in the structuring and part design operations.
- To support teaching in this area by agreeing upon basic concepts and find ways of training function and property reasoning.
- To master the influences from multi product development, modularisation and platform thinking in the embodiment design process.

The effects of enhancing focus and competences in the embodiment area should be measurable in the following places:

- In the competing edge of products, concerning performance, reliability and value related to functions and properties.
- In the companies' internal efficiency by creating alignment and managing the complexity of embodiment.
- In the external effectiveness of offering users more attractive product-related operations and services throughout the product life phases.
- In the radical reduction of number of design changes from improper change operations and lack of control of the propagation of changes into the property field of the product.
- In the efficiency of growth of a company's product range and versatility.
- In product recall reduction.
- In the reduced repetition of design work.
- In the efficiency in design communication and task specification.
- In better informed trade-off decisions for both parts and structures, enabling trade-off of sub-system level efficiency for greater system level efficiency.

Of course these expectations are dreams from our side and the deficits are postulates for which many scholars work hard to try to deliver such solutions. However, for now at least, this remains one of the greatest challenges of '*engineering* design research'.

2.11 Conclusion

Even if the use of information technology has revolutionised designing and today is indispensible, many remaining problems can't be resolved by the regulation of streams of information, but need a closer understanding of the matters. It is our observation that embodiment and detailing is surprisingly a theory and language empty area where reasoning about function, structural and property aspects is unsupported and the design process is actually not well understood.

Our article is an answer to Professor Birkhofer's demand to elaborate on challenges in design research. We have answered related to a sub area of design research, namely embodiment, based upon personal opinions, a personal way of articulating embodiment design and a none-documented set of statements on state of the art and challenges. We hope the article will be read for inspiration and that researchers will see challenges in verifying or falsifying postulates and maybe work on what we see as challenges in embodiment design.

2.12 Afterword

During the career of Professor Birkhofer a great paradigm shift has occurred, from design practice to design research, from practice knowhow to models, methods and knowledge. During this time we have faced changes due to globalisation and the dramatic impact of both the technological and the digital information age. Despite these crucial times in the history of engineering design, huge headway has been made. Design has a clear and established place in product and technology development and the explosion of work describing the design and its processes have enabled communication and educational improvements both within and across its disciplines.

It is with great pleasure we contribute to this book on design research. One of the weaknesses of our young research area is that we have not yet found a way to communicate of our belief on central contributions, identify a powerful foundation and identify important directions of development. It is the merit of Herbert Birkhofer that he is in the front of challenging our research activities, requesting research consolidation and showing new directions, especially in the engineering oriented dimension of design and understanding of human design.

We believe this collection will be a valuable platform for development, not a closing balance for a period of efforts.

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Chapter 3

Methodical Support for the Development of Modular Product Families

D. Krause[1] **and S. Eilmus**[1]

Abstract To offer individualised products at globally marketable prices, Institute PKT's integrated approach to developing modular product families aims to generate maximum external product variety using the lowest possible internal process and component variety. Methodological units of product program planning, design for variety, life phases modularization, module lightweight design and process-oriented product development support the creation of modular product families during the product development process.

3.1 Introduction

For new products already during product development the extent to which a product meets the challenges of modern market situations is determined. It is important to address contradictory competitive factors and developments. "The change from the seller's market to the buyer's market […] [along] with the result of an excessive number of product variants and […] intense price competition does not mean that this has to hold true for the future […]" (Deutsche Akademie der Technikwissenschaft (acatech) 2010). This statement contrasts with *individualization*, a megatrend with consequences for product innovation and development. Today, this trend is reflected in the conflicting customer requirements of low prices and personalized products.

At first glance, these two scenarios result in two different strategies for future product development. To offer competitive prices the aim is to develop standard mass-market products - the focus being on the advantage of large quantities of the same products. On the other hand, to be able to make a profit, a high number of individualized products can be a successful way to meet individual customer requirements. Both strategies involve chance and risk. In product development, the strategy for developing modular product families is ideal for combining the advantages, i.e. individual customer demands, with low costs to be well prepared in the future.

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The aim of developing a modular product structure for a product family is to maintain the external variety required by the market and reduce internal variety within the company to control, reduce or avoid the associated complexity of corporate processes in product development. A major advantage of this strategy is the larger quantity of standard modules derived that contribute to cost reduction, for example, with better utilization of economies of scale and learning curve results, especially in procurement, production and assembly. Modular structures provide the opportunity to parallelize any processes, e.g. to develop different modules in parallel or to test or produce them separately.

To better understand the special characteristics of modular products, essential features will be discussed to derive a definition.

3.2 The Five Attributes of Modular Products and their Effects

The literature defines modularity and modularly structured products expansively and in various ways. A comprehensive definition permits the description of common attributes of modular products (Salvador 2007):

- *Commonality of modules*: Components or modules are used at various positions within a product family.
- *Combinability of modules*: Products can be configured by combining components or modules.
- *Function binding*: There is a fixed allocation between functions and modules.
- *Interface standardization*: The interfaces between the modules are standardized.
- *Loose coupling of components*: The interactions between the components within a module are significantly higher than the interactions between components of various modules.

Figure 3.1 is a summary of the five attributes of modular product structures. These attributes of the modularity are characteristics that can apply to a product in various forms and degrees. Just as these attributes are gradual, modularity is a gradual characteristic of a product as well. Consequently, the aim of modularization is not the development of a modular product but the realization of a suitable degree of modularity that has been adapted to the corporate strategy.

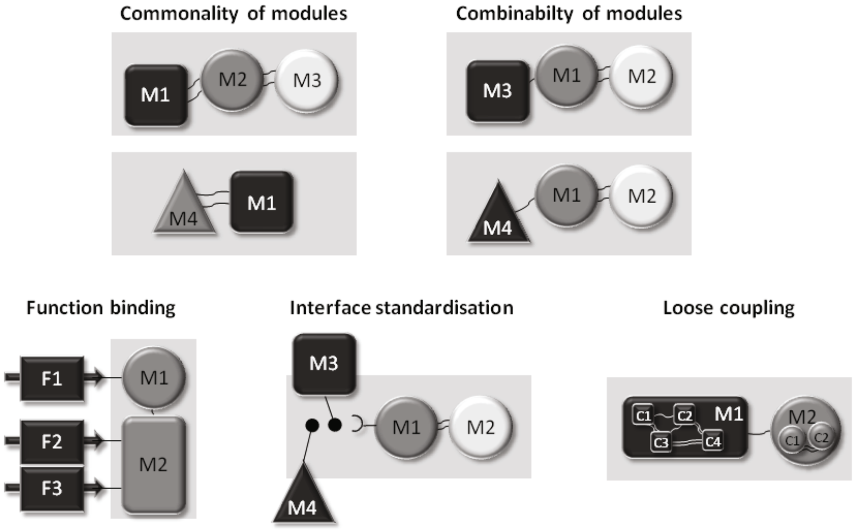
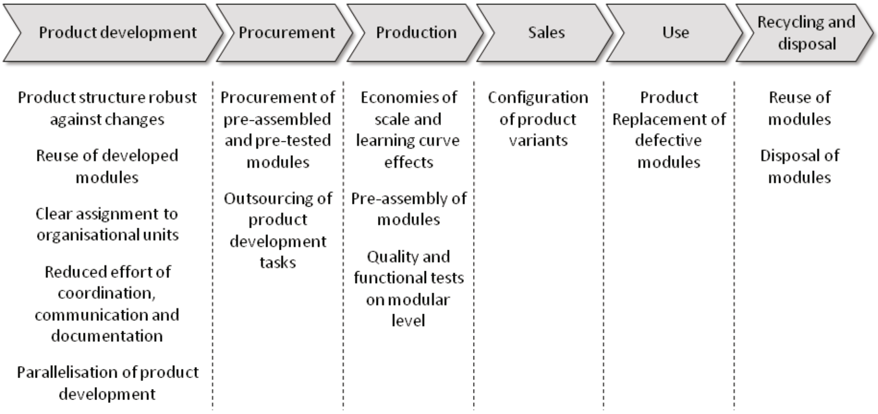


Fig. 3.1 Attributes of modular products (F: Function, C: Component, M: Module)

The modular structure of products and product families can have advantages in every life phase of a product (figure 3.2). The potential and limitations of modular product structures have to be considered. The modular structure of a product may inhibit the optimization of the overall function of each individual product variant. This results in risks in the modularization, such as overdimensioning, additional interfaces and a lack of product differentiation for the customer.



Product development	Procurement	Production	Sales	Use	Recycling and disposal
Product structure robust against changes Reuse of developed modules Clear assignment to organisational units Reduced effort of coordination, communication and documentation Parallelisation of product development	Procurement of pre-assembled and pre-tested modules Outsourcing of product development tasks	Economies of scale and learning curve effects Pre-assembly of modules Quality and functional tests on modular level	Configuration of product variants	Product Replacement of defective modules	Reuse of modules Disposal of modules

Fig. 3.2 Advantages of a modular structure in the product development process

Analyzing the potential and limitations of modular product structures shows that during development of modular products the degree of modularity chosen has to take full advantage of the potential of modular product structures within the company-specific goals and avoid negative effects.

3.3 Strategies for Controlling External Variety

To control the variety demanded by a broad spectrum of customers, companies can follow product-based and process-based strategies, or combinations thereof, as shown in figure 3.3

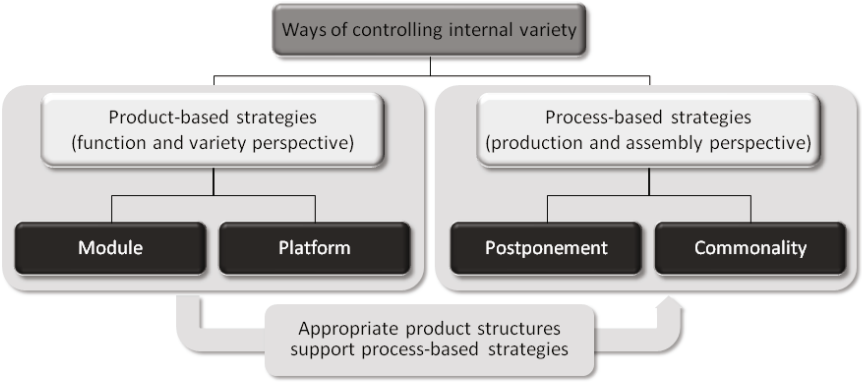


Fig. 3.3 Product-based and process-based strategies for controlling internal variety

As well as the strategy of providing a modular product family, product-oriented strategies also include the *platform strategy*, which is an expansion where a platform, as a basic module applied to a product family, is defined as standard.

A modular product structure adapted to corporate goals allows orientation towards complexity-reducing process strategies, as they are closely related to the product structure. *Process commonality* describes the strategy of using the same processes for different products to counteract the variance of a product family by unifying the processes. A *Postponement* strategy provides the greatest possible part of the production process, independent of variants. Postponement describes the delay of processes that are variant. This means that the variant-specific process steps are at the end of the process, if possible. Figure 3.4 is a schematic overview of both these process strategies.

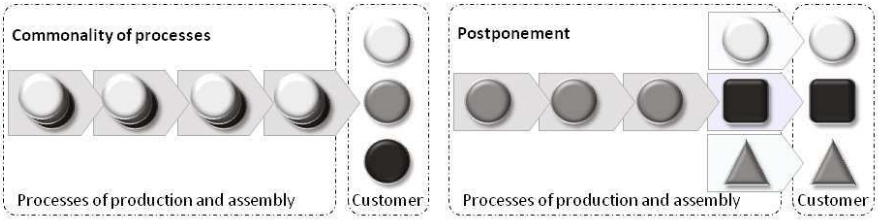


Fig. 3.4 Process commonality and postponement strategies

3.4 PKT's Integrated Approach for Developing Modular Product Families

A goal-oriented, methodical approach is necessary to capitalise on the potential described above. To do this, there are predominantly three steps for existing modularization methods (Blees and Krause 2008):

1. Decomposition of the product up to the level of the components.
2. Analysis and documentation of the components and their couplings.
3. Analysis of the possibility of reintegrating the components.

Other highly matrix-oriented approaches, such as the Modular Function Deployment and the Design Structure Matrix, have developed, and will be further developed at a number of institutes, as summarized in Kipp (Kipp et al. 2010a).

In contrast, PKT has developed an integrated approach that goes beyond mere modularization, as the development of modular product families can be achieved in ways other than just new grouping or regrouping of the components. As well as modularization, it includes a more strategically focussed approach, product program planning, and design for variety which means the redesign of components in terms of variance reduction and allows the integration of new requirements or functions. These steps are followed by the actual modularization, which takes into consideration all specific requirements defined by the relevant product life phases and is therefore called life phases modularization.

To carry out a process-based evaluation of alternatives for modular product structures for a product family, an important methodological unit is the integration and coordination between the product development processes with respect to commonality, the postponement strategy and the product architecture (figure 3.5).

An increase in weight reduction has a newly created term: *module lightweight design*. Weight is given priority as an additional dominant boundary condition if the development of lightweight products, such as aircraft cabin components, is of primary concern.

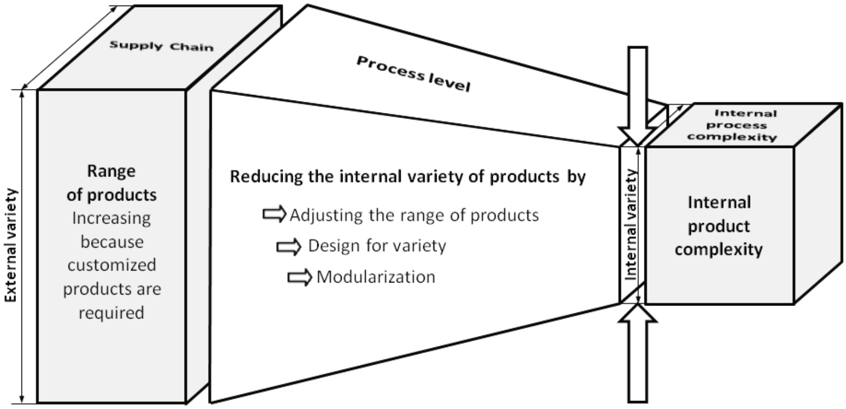


Fig. 3.5 Integrated PKT approach for developing modular product families

3.4.1 Product Program Planning

During the stage of product program planning, the products and variants to be produced are defined at a product-strategic level. First, the existing product program of the company is analyzed. To do this, a visualization tool is developed at PKT that displays the hierarchical structure and quantitative dimensions (number of units, volume of sales), as shown in figure 3.6 (Jonas and Krause 2010).

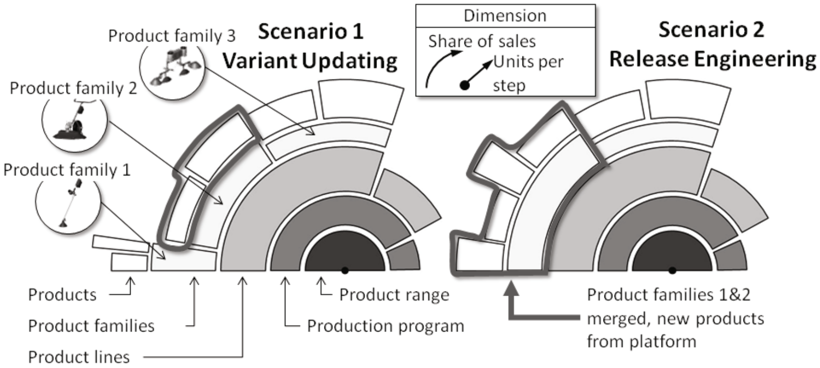


Fig. 3.6 Scenarios of product program planning (Jonas and Krause 2010)

Based on this, alternative product program scenarios are developed based on customer requirements and business strategies, which determine the future composition of the product program. During the subsequent technical evaluation, scenarios for the creation of platforms, spanning the product families, and modules purchased are evaluated. Based on this evaluation, the final concept for the composition of the product program is chosen.

3.4.2 Design for Variety

Design for variety brings the product families under consideration closer to an ideal, allowing a description to be made. This ideal is defined by four characteristics:

1. Differentiation between standard and variant components.
2. Reduction of the variant components to the carrier of a differentiating attribute.
3. One-to-one mapping between differentiating attributes and variant components.
4. Complete decoupling of variant components.

In the first step of the method, the external market-based and the internal company variety of the product family are analyzed (figure 3.6). Analysis of the external variety is supported by a tree of differentiating attributes. This tree visualizes the selection process of the customer.

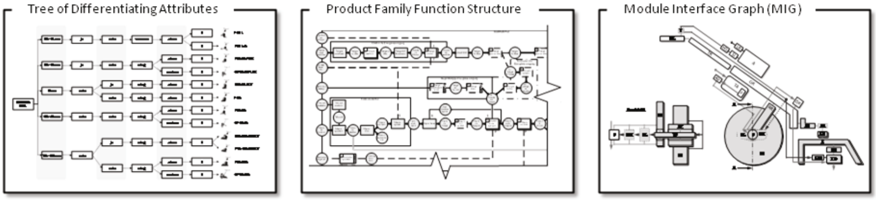


Fig. 3.7 Partial models for the analysis of product variety (Kipp et al. 2010a)

Internal variety is analyzed at the levels of functions, working principles and components. The variety of functions is shown in an enhanced function structure that makes representation of variant and optional functions possible. The variety of working principles is determined from sketches, where the necessary variance of the functional elements is marked in colour. The specially developed Module Interface Graph (MIG$^{©}$) is used to analyze the variety of components (Blees and Krause 2008). The MIG provides a schematic representation of the rough shape and arrangement of the components and their variance, as well as the structural connections and the power, material and information flows, which enables them to be taken into consideration when defining modules and reducing variant components.

All relevant information for carrying out design for variety for preparing constructive proposals is visualized in the Variety Allocation Model (VAM$^{©}$) (Kipp et al. 2010a, Kipp et al. 2010b). The connections between the levels demonstrate the allocations between differentiating attributes, functions, working principles and components (figure 3.8). In this way, the VAM allows the analysis of the degree of fulfilment of the four ideal characteristics. For variant conformity, any weak points in the design can be identified at all levels of abstraction. Thus, VAM is the basis for solution finding and selection of solutions in the methodological unit of design for variety.

The result of this methodological unit is a newly designed set of components with an increased number of standard parts. In addition, multiplication effects of the variance are avoided, with the result that each component is required in a small number of variants. Moreover, the simplified allocation structure between components and differentiating attributes simplifies the variant configuration.

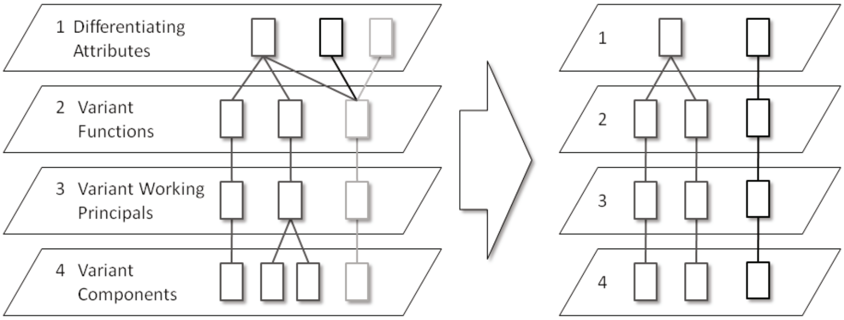


Fig. 3.8 Applying the Variety Allocation Model (VAM) (cf. Kipp et al. 2010a)

3.4.3 Life Phases Modularization

The aim of the life phases modularization is the development of modular product structures using the results of the product design for variety for each individual relevant product life phase, as well as checking their consistency and adjustment to a continual module structure. Product structure requirements can be better met by considering different product structures for individual phases. The procedure is divided into the following steps:

1. Development of a technical-functional modularization
2. Development of modularizations for all relevant product life phases
3. Combination of modularizations
4. Derivation of the modular product structure

The starting point is the technical-functional modularization of the product development phase. Modules are provided that are largely decoupled to reduce the complexity of the development task and allow parallel development of modules. The development of modularization perspectives of all relevant product life phases is made by module drivers associated with the individual life phases. For instance, the production phase is mapped by the module driver ‘Separate Testing’ (figure 3.9).

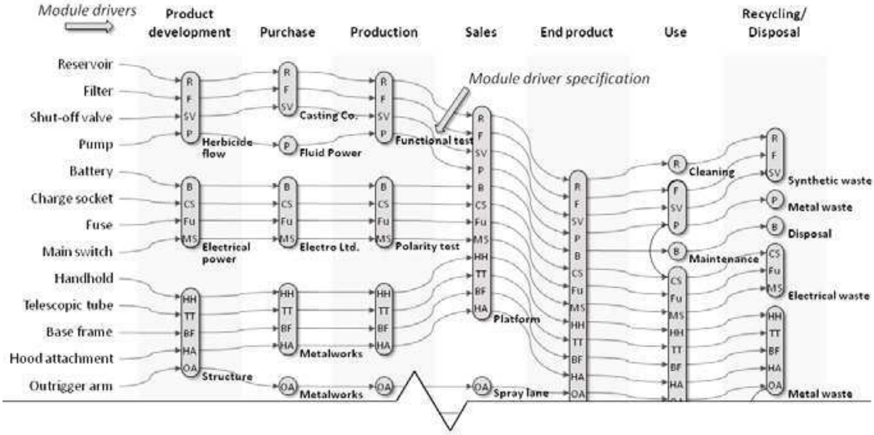


Fig. 3.9 Module driver and module driver specifications allocated to components in the Module Process Chart (MPC) (Blees et al. 2010)

The module drivers are stipulated by concrete specifications for the development of modules. In the module driver ‘Separate Testing’, the tests to be carried out demonstrate the product-specific specifications. In network diagrams, these specifications are linked to the components of the product. The preparation of modules is made by grouping the components that relate to a common module driver specification into one module. Subsequent to the development of modular product structures for the individual life phases, the modularizations are visualized in a MIG to allow consistency checks between the different life phases and demonstrate any conflicts. It was found that it is not necessary to develop the same module structure for all life phases that cannot be realized because of the different and contradictory criterions. Rather, it is important that the module structures of the individual phases are adapted and continuous but not 100 percent congruent. For assembly, it may be advantageous to install a module that is as large as possible. For purchase, it may be necessary to buy this module in the form of smaller modules from different suppliers which, in case of a well-adapted structure, must not be contradictory. The *Module Process Chart (MPC)* transparently combines the various perspectives of different life phases and makes the coordination process more clear (Fehler! Verweisquelle konnte nicht gefunden werden.). Finally, the product structure can be derived (Blees et al. 2010).

3.4.4 Process-Oriented Product Development

Since the focus of the individual methodological unit is mainly on the products and the product structure, there should be more priority given to process-oriented product development. Industry case studies could be made of the effect that small modifications based on customer requirements have on the business process of a company.

In variant management, companies often carry out an ABC analysis to find out which variants are infrequently required by the customer to eliminate them. If, however, these product variants involve no or only an insignificant additional effort in the production process and, consequently, involve no or only very low costs and the direct costs, if necessary, can be shared by the customers, those variants should not be eliminated. Therefore, the significance of a product variant is from the effort and the process variety in the business process and decides whether the variants are reduced or controlled (figure 3.10). To this end, the requirements of the level of product structure, corporate processes, and the supply chain, and their interactions have to be taken into consideration (Brosch and Krause 2010).

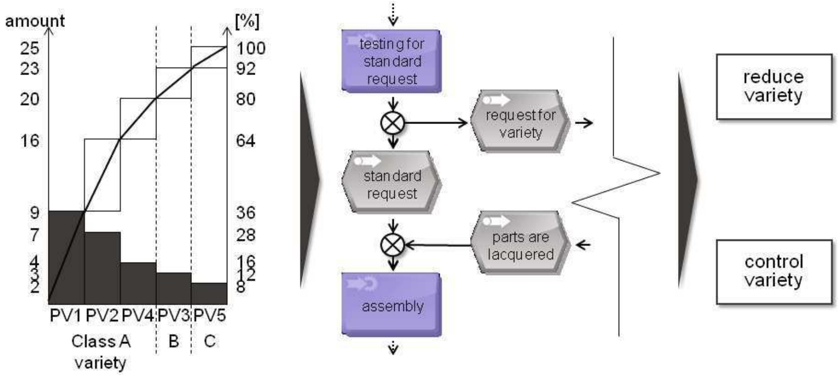


Fig. 3.10 Significance of product variants (Brosch and Krause 2010)

3.4.5 Module Lightweight Design

To be able to meet weight requirements, the module lightweight design brings competing requirements between lightweight design and modularization into line with one another and promotes synergetic effects.

Based on the MIG, the modules are optimized for weight, taking advantage of the fact that a modular product structure permits strong couplings within the modules so that savings in weight can be realized by integral construction and the possibility of integrating functions. Applying a detailed analysis to all modules accentuates the weight-critical modules; the whole product family is especially sensitive to a weight change of these modules. Increases in weight in these modules often spread to other modules. Thus, the weight of this module is increased and, because of the weight-induced load increase, other modules have to be adapted as well. This effect is intensified by the creation of variants. Considering the manufacturing possibilities and costs, the modules material lightweight design and weight structures, which are identified as being critical according to the categories of system lightweight design, are especially optimized for their weight (Gumpinger et al. 2009).

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Chapter 4
Risk-Driven Design Processes: Balancing Efficiency with Resilience in Product Design

J. Oehmen[1] and W. Seering[1]

Abstract Current design methods and approaches focus on increasing the efficiency of the product design system by, for example, eliminating waste and focusing on value creation. However, continuing failures in the development of complex, large scale products and systems point towards weaknesses in the existing approaches. We argue that product development organizations are hindered by the many uncertainties that are inherent in the process. Common management heuristics ignore uncertainty and thus overly simplify the decision making process. Creating transparency regarding uncertainties and the associated risks (i.e. effect of uncertainties on design objectives) is not seen as an explicit priority. Consequently organizations are unable to balance risk and return in their development choices. Product development processes do not emphasize reduction of risks, particularly those risks that are apparent early in the process. In addition, the resilience of the PD system, i.e. its ability to deliver on-target results under uncertainty, is not deliberately designed to match the level of residual uncertainty. This chapter introduces the notion of Risk-Driven Design and its four principles of 1. Creating transparency regarding design risks; 2. Risk-driven decision making; 3. Minimizing uncertainty; and 4. Creating resilience.

4.1 The Challenges of Complex Product Design Projects

The development of complex products and systems continues to pose significant challenges for companies. For example, the US Aerospace & Defense industry (GAO 2010) is facing massive cost and schedule overruns by 45% and 22 months respectively. This results in a projected cost overrun of $296 billion for the largest 96 systems that are currently being developed (which is more than the annual GDP of South Africa, Finland, or Portugal). These problems persist, although there is a host of product design and development processes and methods that place significant emphasis on high efficiency (Krishnan and Ulrich 2001), i.e. ge-

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nerating a high-performing product or service with minimum cost and within minimum time.

Conventionally, emphasis is placed on increasing the efficiency of the design process, that is minimizing the amount or quality of input factors while maximizing the output. The relevant attributes of the output (i.e. product and/or service) are characterized by the trade-off among different objectives (Griffin and Page 1996), such as time (e.g. design project schedule, time to market), cost (e.g. design project budget, unit production cost) and quality (e.g. product performance or reliability). The overall goal is to make effective trade-offs among quality, cost, and time, both in terms of efficiency – reaching a higher overall ‘average’ among the objectives – as well as in terms of explicitly strengthening one of the objectives at the expense of the others. While some approaches acknowledge uncertainty and probability in the way that the achievement of performance objectives is modeled (most notably Design for Six Sigma), PD projects are generally planned based on static and ‘foreseeable’ point estimates.

4.2 Uncertainty and Risk in Product Design

Uncertainty and uncertainty reduction are at the heart of every product development and design project. Designers generate information, transform imprecise into precise information, and gradually reduce uncertainty (Sommer et al. 2008). The theory of bounded rationality explains how the decision making of individuals is always subject to uncertainty (Simon 1997). Extending this theory to organizations (for example in the theory of costly rationality, Radner 2000), it becomes apparent that in team and group settings uncertainty is even more relevant due to costly (and therefore limited) communication processes that are necessary to reduce it. There is a rich literature stream attempting to classify and describe different types of uncertainties (Halpern 2005, Knight 1964, Lindley 2006; Morgan and Henrion 1992, Paté-Cornell 1996, Taleb 2010, Pich et al. 2002, Chalupnik et al. 2009, de Weck and Eckert 2007, McManus and Hastings 2005). These classifications for example include the three categories of ‘known uncertainties’ (known probability distribution), ‘Knightian uncertainty’, or ‘ambiguity’ (unknown probability distribution) and ‘Black Swans’, ‘wicked problems’ or ‘unknown unknowns’ (unforeseeable uncertainty, i.e. even the fact that there is an uncertainty in the first place is not known). Other classifications for example differentiate regarding the origin of the uncertainty, e.g. factors endogenous to the PD process (technology and process execution) and exogenous factors (process environment: market, user, culture)

Following the ISO 31000, we understand risks as the “effect of uncertainty on objectives” (ISO 2009). Risks are therefore defined as the quantified impact of uncertainties on the objectives of the PD project. This general definition of risk can be concretized in a number of ways, their merit depending on the circumstances and goals of the risk analysis (see for example Kaplan and Garrick 1981, Haimes 2009, Paté-Cornell 1996). The underlying mental model is that of probability-distributed input factors leading to a probability-distributed achievement of objectives. In this context, risk can be understood in various ways:

- as the probability of failure to achieve a specific target;
- as the maximum possible deviation from an objective for a project;
- as a probability-weighted deviation from an objective, either as a point estimate of a single impact and probability pair or as the integration of a probability-distributed objective function; or
- as the variance from a mean value for achieving an objective.

As risks are functions of both the uncertainty of input factors and their impact on PD objectives, a number of risk taxonomies are possible. They can be structured along the input factors (e.g. technology risk, process risk, customer requirements risk), or along the objectives that they impact (e.g. cost risk, schedule risk, performance risk). Also, risks are linked in complex causal networks (e.g. technology uncertainty leading to schedule slip leading to cost overrun), making it often necessary to discuss them as part of larger cause-and-effect networks of risks, where uncertainties propagate over several levels until impacting an objective, which may in turn impact other objectives.

In the following, we give some examples of risks in product design structured along uncertainty in the input factors of the PD system. As uncertainty can affect every element of product design, this list is necessarily incomplete:

- Company-internal uncertainties: Uncertainty exists regarding the effectiveness of new development processes (e.g. ability of review processes to catch errors).Uncertainty also arises in communication processes regarding both the scope (completeness) as well as the quality (correctness) of communicated information. This is related to uncertainty in the coordination of work among individuals or groups. Uncertainty may also arise regarding the overall status and progress of the project. This leads to uncertainty regarding planning and forecasting, which determines the level of uncertainty of target levels for different objectives. Uncertainty surrounding the capabilities and productivity in engineering has a significant effect on cost, schedule and performance.
- Supplier uncertainties: As significant parts of the value creation in all life cycle phases are executed by suppliers, uncertainties regarding supplier performance during the development process can cause performance, schedule as well as cost risks.
- Customer requirements uncertainties: Both customers' uncertainty regarding their needs and the uncertainty with which these needs are understood by the project team have significant impact on the project performance.
- Market uncertainties: Environmental factors, such as demographic changes (e.g. aging population) or social trends (e.g. concerns regarding global warm-

ing), as well as actions by competitors (e.g. pricing strategy or new technology introduction) can significantly alter target specifications.

- Technology: Technology uncertainty affects an array of product outcomes. For example, technology maturity affects the performance reliability under field conditions. Systems integration maturity affects overall system performance and reliability. Production system maturity affects cost and lead time for manufacturing, and service system maturity affects operation and maintenance cost.

Risk management processes and methods have emerged as distinct management practices and foci of research (Oehmen et al. 2010, Sommer et al. 2008). Based on the above discussion as well as a review of the risk management literature, we advocate the integration of these methods directly into the design process via Risk-Driven Design, described below.

4.3 Risk-based View: Risk-Driven Design

Risk-Driven Design places a different emphasis on the management of the design process than conventional efficiency-driven design (see figure 4.1).When the design process is driven by the intention to manage risk, uncertainties and their effect on the objectives are identified and quantified. Decision making then focuses on risks,usually the most critical first. This is done by reducing the level of uncertainty as much as reasonable and then creating a resilient PD system that can absorb the residual uncertainty to achieve the objectives within the target range.

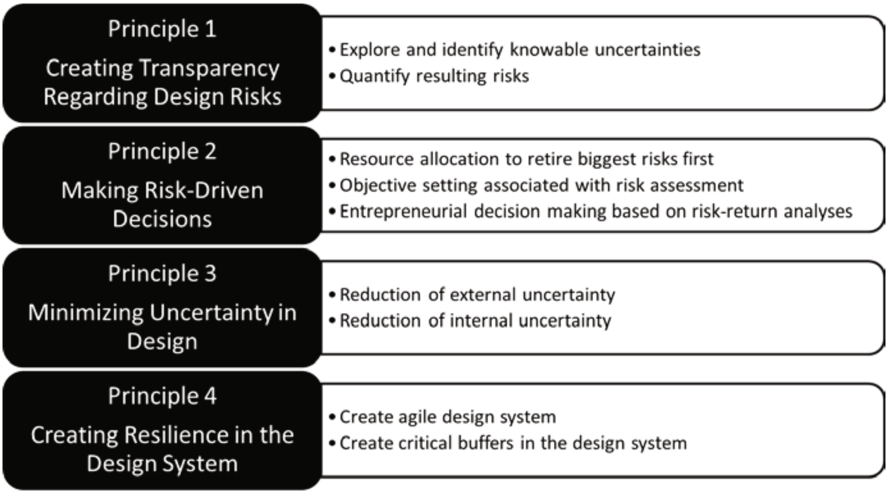

Fig. 4.1 The four principles of risk-driven design

Principle 1: Creating Transparency Regarding Design Risks

The first step in creating transparency regarding design risks is the identification of uncertainties. The second step is to bring clarity to understanding of the identified uncertainties by quantifying them.This can be done to different degrees. Purely verbal descriptions of uncertainties without the possibility for quantification represent the lowest level of knowledge about an uncertainty. Point estimates of uncertainties and their consequences represent the next higher level of fidelity, for example a 30% probability of a $1 million penalty payment. Continuous probability distributions – for example regarding workforce productivity – offer the greatest amount of information. However, all descriptions of uncertainty are only as reliable as the input data they are based on, whether it is expert opinions, simulation models, or historic data with limited applicability to the future.

Principle 2: Making Risk-Driven Decisions

Having transparency regarding the different risks in a project yields several benefits in itself:

Transparency allows managers to prioritize their time and resource allocation to address the largest risks first.

When objectives are set, transparency enables the decision makers to consider the associated probability of success. This helps to set more realistic objectives. It also helps to ensure that planning forecasts (e.g. cost and schedule estimates) are all based on the same confidence level and therefore comparable.

Similarly, when trade-offs are made, decision makers have an additional degree of freedom: Every trade-off between objectives is associated with a corresponding level of risk – specifying high cost and long lead time for a complex system is much less risky than targeting the same system to be a low-cost, short lead time development. It becomes transparent how ambitious a certain set of objectives is.

Transparency enables determination of risk-return trade-offs, creating the opportunity for entrepreneurial decision making: High risk – high return options (e.g. choice of high performing new technology) can be balanced with low risk – low return options (e.g. established medium-performance technology), low risk – high return options can be favored and high risk – low return options eliminated. This will yield a balance of risk taking and performance between the different components of a product and/or service.

This will ultimately allow creation of better design project portfolios on the corporate level, as ‘risky’ high risk – high return projects can be balanced with ‘sure bets’ of low risk – low return projects to achieve an overall optimum risk-return balance for the company.

Principle 3: Minimizing Uncertainty in Design

In order to actively manage risks, managers have two fundamental options: reducing the uncertainty underlying risks and therefore their underlying causes, or making the PD system resilient against uncertainty, that is enabling it to achieve its objectives given a range of input factors.

As discussed above, uncertainty can be reduced, but never completely removed. In the case of product design, we argue that most engineering activities focus on the reduction of uncertainty, and Risk-Driven Design provides a framework for a more guided and focused uncertainty reduction.

The reduction of the overall risk exposure of a project can be used as an important key performance indicator, to incentivize retiring significant risks as early as possible in the design process, instead of succumbing to the (natural) inclination of postponing dealing with them as long as possible, leading to sudden deviations from objectives such as delays and cost overruns during the late project phases.

Principle 4: Creating Resilience in the Design System

Uncertainties can be reduced to some extent; some easily and cost efficiently (e.g. internal uncertainties due to factors that are under the direct control of the company); some with more effort (e.g. external uncertainties from the project environment).Some cannot be influenced at all (e.g. natural catastrophes or residual uncertainty due to bounded rationality). At any rate, every product design project will be facing a residual amount of uncertainty that must be dealt with. The ability of the PD system to deal with this uncertainty can be broken down into two categories: agility, i.e. the ability to respond effectively to unexpected events (Chalupnik et al. 2009), and robustness, i.e. mechanisms to absorb process deviations so that project outcomes remain within the target range, e.g. through buffers.

Agility describes the ability of the PD system to deliver stable performance under varying circumstances. This includes swiftness, the ability to detect errors quickly and plan and take corrective action, for example through unbureaucratic change management; cost efficiency, the ability to accommodate changes at low cost, for example through properly aligned organizational and supply chain incentives; flexibility, the ability to change objectives, for example through regular customer integration and consultation; and versatility, the ability of the PD system to process unexpected challenges, for example due to a broadly skilled workforce or adaptable development processes.

Buffers can fall into several categories: There can be buffering for each objective, e.g. financial buffers (more financial reserves than needed according to plan), schedule buffers (schedule reserves), and performance buffers (e.g. redundancy or overengineering). Buffers can also be created at lower levels, for example by holding excess capacity (e.g. testing facilities).

While creating an agile PD system aligns very well with efficiency-driven management styles, the creation of buffers does not. Transparency regarding the projects risk situation forms the basis for making a business case in favor of establishing critical buffers, and against excess buffers.

4.4 Research Agenda

The concept of risk-driven design needs both additional theoretical and empirical research if it is to mature. From a theoretical standpoint, a gap- and overlap-free taxonomy of design uncertainties and risks has to be developed. Also, risk-driven design has to be understood in the context of various design and product development frameworks, for example stage gate models, spiral development, V- or waterfall-models, concurrent engineering, or set-based design. Similarly, the risk management literature has to be explored to transfer relevant processes and methods into risk-driven design. There is also a rich literature stream regarding decision making under uncertainty, as well as the psychological dimension of human perception and treatment of risk and uncertainty that will have to be addressed.

Empirical research has to be done to uncover the current state of practice regarding the treatment of risk and uncertainty in industry. The viability of the four-principles of risk-driven design has to be tested in both in-depth case studies and longitudinal surveys.

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Chapter 5
Methodology and Computer-Aided Tools - a Powerful Interaction for Product Development

H. Meerkamm[1]

Abstract The fundamental bases of modern product development are elements and systems, design methods and computer-aided tools. The interaction between methodology and computer support, mastered by competent engineers, can help to meet the challenges of future product development.

The adaptation of existing methods and the creation of new ones that focus on interaction with computer-supported tools are a necessary and important part of design methodology. Methods that can help use the increasing power and capacity of future computers and allow a holistic view on the complete process of product realization are demanded. This paper describes the potential arising from an effective and powerful interaction between methods and tools. More support in decision-making is needed within the process of product development. Solutions based on an interaction between methods and CAx tools can provide powerful assistance to engineers in this field.

5.1 Introduction

The demand for sophisticated, complex and often individualized products in areas such as traffic, energy, medicine, and the environment will increase in the future global economy. To be successful in these markets, even if the number of competitors is increasing, companies must be able to develop customer-driven, high-quality products.

The need, therefore, is for engineers who are masters in the fields of product development: elements/systems, design methods, and computer-aided tools. The interaction of methods and tools at various steps in the process of product development is an important factor for success. The future development of design methodology will proceed more slowly than the development of computer-supported tools. Nevertheless, precise and sometimes customized interaction between methods and tools will provide engineers with better support in predictive

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engineering and decision-making. There is, therefore, a need to adapt design methods so that they can be used in combination with various CAx tools. The design process is the driver for determining the best method or tool to be used.

This chapter gives an overview of the range of design methods and CAx tools, along with some examples of their successful interaction. The examples form the basis for a brief look at future development.

5.2 The Fundamentals of Product Development

The basic areas of product development are:

- Machine Elements and Systems
- Design Methods
- Computer-Supported Tools

Efficient interaction between these areas is dependent upon well-educated engineers who manage the fields along the whole process of product development and realization. Machine elements offer a huge number of solutions so it is necessary to distinguish between designing with machine elements and the designing of machine elements. Although they represent an excellent stock of solution elements, machine elements are not dealt with in this paper. Rather, the focus is on the interaction between methods and tools, the slaves of engineering masters as well as masters of the process of product development.

5.3 The Interaction between Design Methods and Computer-Supported Tools (CAx Tools)

Developing good products involves examining and developing a holistic understanding of the entire product cycle from inception to disposal, also known as “cradle to grave”. In reality, there is a wide variety of proven and effective design methods and CAx tools available. An engineer can choose the method or tool most appropriate to the task and stage of the product development process.

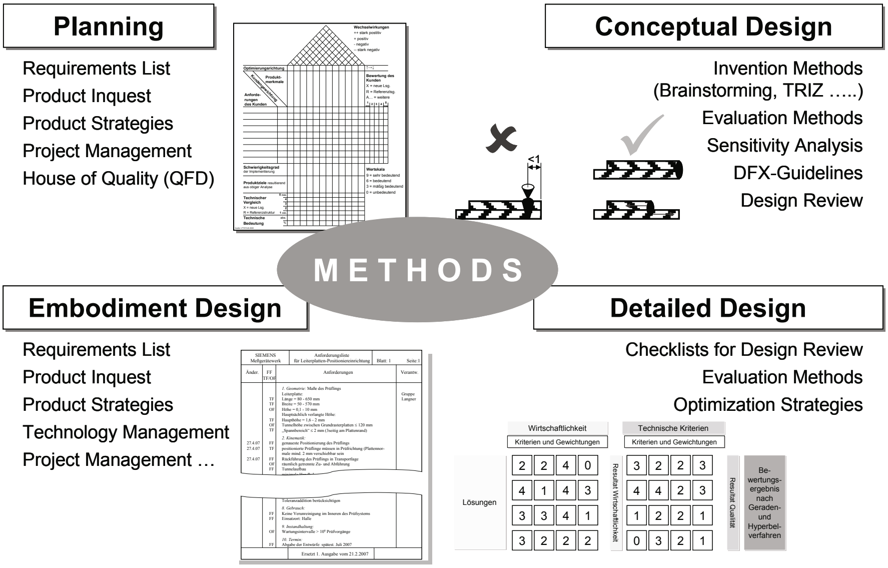


Fig. 5.1 Overview of Design Methods

Engineers benefit from the large number of mature design methods. While there is no universal method, there is a variety of different methods available for the main stages of the product development process: planning, conceptual design, embodiment design, and detailed design.

New methods are being released, e.g. Design Thinking (Brown 2008) and the Design Structure Matrix (Ulrich and Eppinger 2007). They are, however, not a revolution in this field but more of an evolution. The question remains of whether a real revolution can be expected in design methodology or whether the degree of maturity is an indicator of evolutionary development.

In spite of the methodology maturity, there is a lack of method adaption to enable interaction with computer-supported tools. Birkhofer stated “design methods and CAx tools fit together like a key and a key hole”. Nevertheless, there is a demand for adaption in both fields to obtain greater efficiency in the interaction between methods and tools. The fitness of this combination has to be improved.

Some researchers believe the Finite Element Method (FEM) is the universal calculation tool, others believe there is no universal tool. Many different and powerful CAx tools are available to engineers in the process of product development. The tools belong to and are powerful in different stages of the design process. Their selection and use is process driven.

Because of the dynamic development of information technology (development in the capacity and speed of both hardware and software is steadily growing, highly dynamic and far from complete), new tools are developed and existing ones become more powerful.

Although some examples of good interaction exist, a challenge for the future is the improvement of interaction between methods and tools.

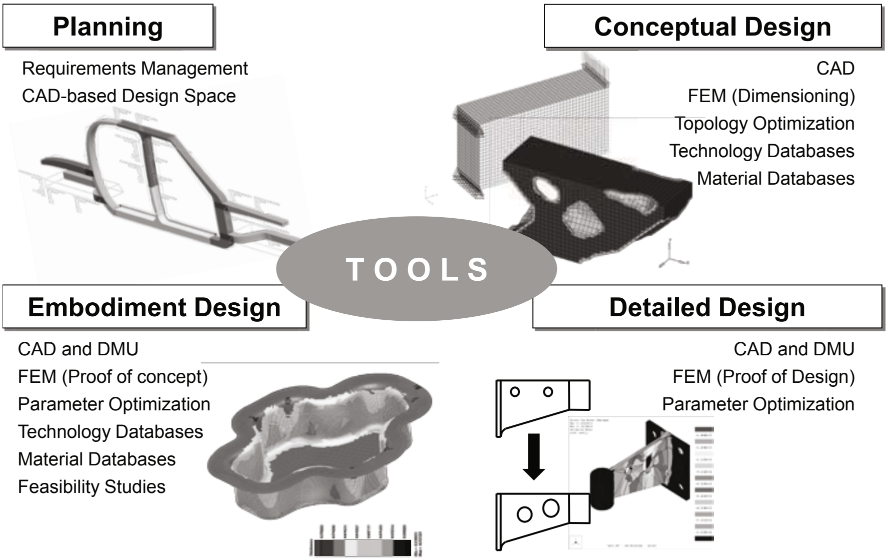


Fig. 5.2 Overview of Computer Supported Tools

5.4 Examples of Successful Interaction

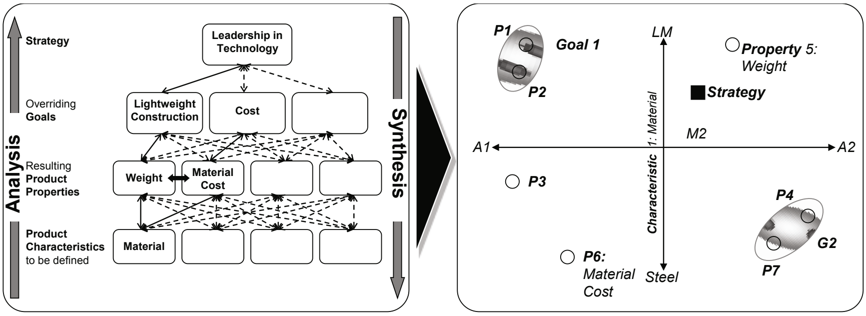
The process of product development is information processing combined with continuous decision-making. It is a repetitive interaction between synthesis and analysis processes. Designers need methods and tools to analyse the solutions from different perspectives, and demand tools that allow prediction of the behaviour of the product before it happens.

The following examples are of a holistic approach to DFX, using design methods and simulation tools in Design for Production, the visualization of tolerances and detailed modelling of the design process.

5.4.1 DFX

Engineers make decisions about product and process characteristics and want to know the effect that these decisions have on the product properties and behaviour as soon as possible. In DFX (Design for X; X = production, assembly, use, recycling, cost, etc.), this is a challenging task because DFX is “making decisions in product development related to products, processes, and plants” (Huang 1996).

The Xs are often interdependent and sometimes contradictory. It is nearly impossible for the product developer to survey the complete field: they need assistance from suitable methods and tools to achieve the right balance in this multi-criteria decision-process. Bauer (Bauer 2009) had an interesting way of combining design methods with computer-aided tools. He could demonstrate that the combination permitted better mastery of the huge field of DFX.



Decisions in Product Development

Support by Interactive Visualisation

Fig. 5.3 Support of Multi-Criteria-Based Decisions in DFX

Because of the mutual dependencies within the network structures of products and processes, decision-making is complex and difficult. There is no ideal solution. The goals of DFX must balance carefully. They depend on each other and are sometimes in conflict. Bauer created an information system and an intuitive, interactive visualization of interdependent product properties, underlying characteristics and superior goals. All dependencies can be visualized and the engineer can define a strategy. This approach allows a holistic understanding, management and communication of complex decision tasks in the design process.

5.4.2 Calculations and Simulations in Design for Production

Stockinger’s thesis (Stockinger 2010) demonstrated that the use of a well-adapted set of computer-aided tools and design methods is effective support for design for production and tolerance analysis. The effects of product development and production/assembly are the focus of this work.

Table 5.1 Overview of the Methods and Tools Employed in the Integrative Simulation Concept

Process Step	Task	Methods	Tools
1a. FE-based sheet metal forming simulation of the production process steps	Statistical analysis of the forming process	Sensitivity analysis	Pam Stamp 2G (Stockinger and Meerkamm 2009a)
		Latin Hypercube Subsampling	MATLAB (MATLAB Documentation 2009)
		Response Surface Method RSM	MATLAB (MATLAB Documentation 2009)
1b. Sequential Tolerance analysis of the production process steps	Statistical analysis of the turning/milling process	Monte-Carlo Analysis Sensitivity Analysis HLM Simulation	Teamcenter Visualization VisVSA (Stockinger and Meerkamm 2009b)
2a. Analyse deviated part geometry	Evaluation and transformation of Part Key Characteristics	Trust-Region-Reflective Optimization Capability Indices C_p, C_{pk}	MATLAB (MATLAB Documentation 2009)
2b. Analyse deviated part geometry	Evaluation and transformation of Part Key Characteristics	Capability Indices C_p, C_{pk}	Teamcenter Visualization VisVSA (Stockinger and Meerkamm 2009b)
3. FE-based compliance simulation of the assembly	FE-modelling and calculation of the assembly steps	Simulation approach according to Liu	Altair HyperWorks
4. CAT simulation for the analysis of system behaviour	Statistical modelling of the assembly process	Monte Carlo Analysis Sensitivity analysis	TC Vis VisVSA with FE-integration (Stockinger and Meerkamm 2009b)
5. Analyse deviated assembly geometry	Analysis and documentation of the statistical Key Characteristics	Capability Indices C_p, C_{pk}	TC Vis VisVSA with FE-integration (Stockinger and Meerkamm 2009b)

Table 5.1 (continued)

Process Step	Task	Methods	Tools
6. FE-based loadcase simulation of the assembly	Analysis of the assembly behaviour due to scatter of geometry and loads	Stochastic FEA	MATLAB (MATLAB Documentation 2009)
7. Analysis of deformed, deviated product	Assembly behaviour taking into account deviations	Capability Indices C_p, C_{pk}	Teamcenter Visualization VisVSA (Stockinger and Meerkamm 2009b)

In the process steps and inherent tasks, various methods and tools, such as integrated and linked simulation technologies, were used to predict the product properties and behaviour.

By using these virtual methods, the product function is guaranteed while the interrelation between product development and product realization is considered.[2]

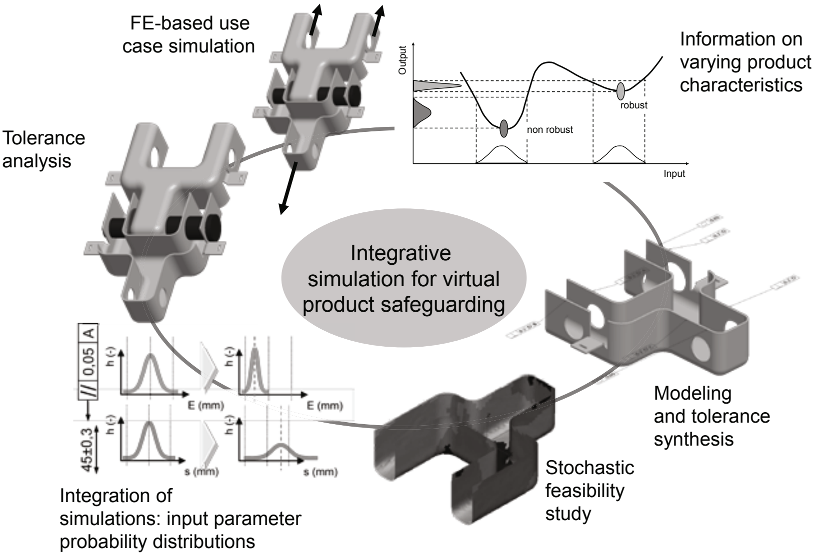


Fig. 5.4 Integrated Simulations for a Virtual Prediction of Product Properties

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[2] Spur (Spur 2010) states that, in future, dealing with design and production simultaneously is a must. This demands effective simulation methods.

5.4.3 Tolerance Analysis/Visualisation

Visualisation is an important factor in tolerance analysis. Designers need the consequences of their decisions on tolerances (form, orientation, location, run-out) demonstrated as soon as possible. Receiving this information after finishing the production or assembly process is too late because the necessary correction costs time and money, whereas a change of tolerances during the design phase is less critical and less expensive.

Modern computer graphics tools and solutions allow tolerance analysis by visualising the consequences of design decisions. For the designer, this is much easier to handle than special documents and print outs of statistical data.

Stoll (Stoll et al. 2009) demonstrated the first step of this philosophy in car body design (figure 5). The gaps between car body panels are an indicator of quality. Based on ideal geometry, the approach fosters the discussion of aesthetics and the distribution of tolerances. The next step in preparation allows non-ideal geometry resulting from simulated production processes, such as sheet transforming processes, to be imported. Through this, it will be possible to choose which deviation is acceptable due to function and aesthetics.

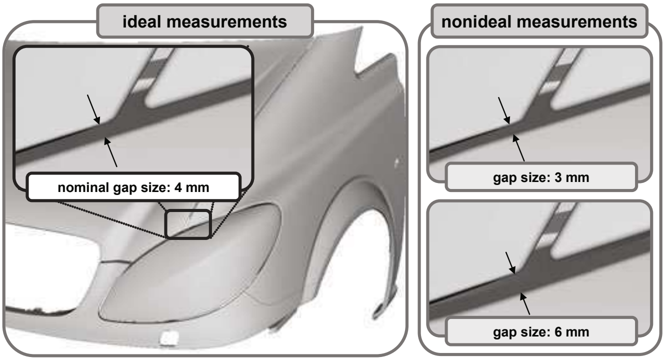

Fig. 5.5 Visualization of Gap Width (Stoll)

5.4.4 Process Modelling

As mentioned previously, selection of the most suitable method or tool is driven by the design process. Therefore, there is a need for more detailed modelling of the design process.

A refined process model was developed in an interdisciplinary research project to enable flexible support of the process of product development by different methods and tools (Meerkamm et al. 2009, Krehmer et al. 2010). This generic product model, structured in three levels, allows the integration and use of diverse design methods, CAx tools and product models. DFX features are supported and access to a knowledge base is prepared. Thus, the FORFLOW process model is a precondition for successful interaction between methods and tools.

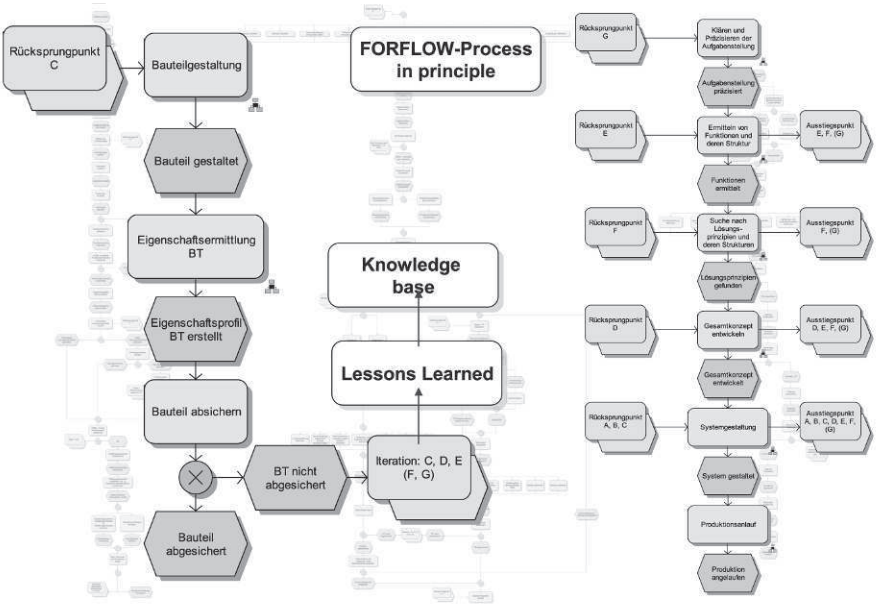

Fig. 5.6 The FORFLOW Process Model

5.5 The Future Development of Methodology and CAx tools

The examples described above demonstrate that good interaction between design methods and CAx tools is very helpful in various problems and tasks.

This is only the beginning; the potential for the future is great. Design methodology and CAx tools were not developed at the same time but could partner well in the future. To do this, the following is required:

- Integration of methods in tools
- Integration of tools in processes on a methodological basis.

The importance of modelling will increase:

- Modelling of products
- Modelling of processes
- The development of design methodology will progress continuously but slowly (as well as new methods, new variants of existing methods will arise, but there will probably not be a revolution).

- The progress in computer support will be much greater (the capacity and velocity of computers will increase quickly in the future).
- The real potential of computer support will only be realised in combination with customized design methods.

5.6 Conclusion[3]

Future success in various markets (e.g. traffic, energy, medicine, and the environment) is reliant on complex and sophisticated products. The development of these products needs a well-balanced and integrated use of design methods and computer-supported tools. Therefore, bringing together both fields is a very important task, needing integration on a methodological basis of methods with tools and tools with the process. Methods and tools must be customized to each other. By doing this, it will be possible, for example, to simulate not only the process of product development, but also the complete process of product realization. In a continuous interaction between synthesis and analysis, engineers will get the information necessary for making their decisions and it will be possible for designers to visualize the consequences of these decisions. All this, of course, needs well-educated engineers with detailed knowledge of both fields, based on sound knowledge of the fundamentals.

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[3] The author thanks Dr.-Ing. Andreas Stockinger (Senior engineer Lehrstuhl Konstruktionstechnik) for fruitful discussions, some input and the necessary technical assistance to complete this paper.

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Chapter 6
A Reuse Design Decision Support System Based on Self-Organizing Maps

J. Feldhusen[1], A. Nagarajah[1], S. Schubert[1], A. Brezing[1]

Abstract This paper demonstrates the advantages of combining computer attributes with human attributes for useful cooperation in reuse design decision making. In this field of design, the final decision is generally made by a human, since they are better at interpreting the structure of the data than a computer, provided that the data is processed and presented in a clear and comprehensible way. A good approach to processing data is visualization, which can be performed by the data mining method Self-Organizing Maps (SOM). SOM can be used to effectively visualize the structures and connections in the available data.

6.1 Introduction

The global economic crisis has shown how important rationalization measures are for successfully continuing business activities (Winter 2008). Experts estimate that in the automotive industry alone up to 100,000 jobs are at risk if companies do not make use of their full rationalization potential to save above-average costs (Winter 2008). These cost savings in the production process may not affect the quality of the product in any way. However, there would be additional spending because of claims for damages caused by malfunctioning products, and a decline in sales because of a loss of image (Bruns and Meyer-Wegener 2005).

A possible way to avoid these is to concentrate on reuse design. Existing products are adapted to new customer requirements without changing the solution principles that have proven successful in practice (Ong et al. 2008).

The biggest challenge in reuse design is recognizing which of the existing product variants has the greatest similarity to the new order. This variant has to be used as the starting point for the design of the new request. In this way, the necessary changes are kept to a minimum and costs are lowered.

Experience has shown that selecting a similar product variant using only on the cognitive ability of a human is not the ideal solution. This is reflected in the cur-

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rent method for selecting a product variant. The engineer usually picks the most recently designed product variant as the starting point for a design, completely avoiding the search for a matching product variant. The engineer needs to be supported by a computer.

The goal of this research is to develop a process to obtain an effective and efficient selection of existing product variants based on product requirements. A computer will be used to prepare the specifications of the requirements so that the engineer can make the best possible choice. When a computer processes the requirements, it is important to present the results graphically to the decision-making person. Scientific work in this field has shown that the human mind is especially effective in organizing and analyzing data when it is presented in a graphic form (Rao 2007).

6.2 Analyzing the Combination between Human and Computers

Companies process data and make decisions. Therefore, it is logical to examine computer use in an optimal selection process. For this analysis, a general scheme has been established to allocate tasks between computers and humans. Based on these results, a systematic search for existing approaches can be made. In developing the procedure, all existing combinations of task sharing in preparing requirements and making decisions between human and computers are elaborated (figure 6.1).

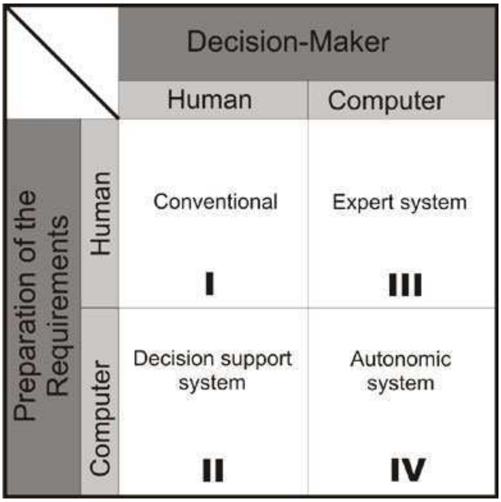


Fig. 6.1 Split of tasks between human and computers

The two areas in which humans and computers can manage tasks individually (Category I and IV) are not considered as being target-oriented, which is why a splitting of tasks between these two has to be the goal (Category II and III). The question remains of how to split the tasks correctly.

The expert systems offer a wide range of possibilities for knowledge representation and inference mechanisms. This is, however, under the condition that humans provide the necessary knowledge. Therefore, the expert system can only be as good as the knowledge provided by the experts. Humans are unable to extract knowledge out of unmanageable data in a system as complex as product development. In reality, humans are able to use information or knowledge from other fields to make a decision (Kurbel 1992). In an expert system, performance rapidly declines when the system operates outside its field of knowledge (Kurbel 1992). Consequently, in Category III neither the advantage of human abilities when dealing with information processing nor the advantage of computers when dealing with large amounts of data are used. This is a possible reason why no expert system for selecting a product variant using specifications was found. The approaches in the category Decision Support Systems (DSS), such as the DeCoDe method (Ott 2009), the FOD (Function-Oriented Design) model (Leemhuis 2005) and METUS (Göpfert 2009), are based on the same principle of linking requirements with product components. The advantage of these approaches is that a comparison is possible because of existing links between requirements and product variant. The question remains, however, of how practical it is to establish such links. The challenge lies in the fact that all knowledge about the product, which in theory needs to be represented by the link between requirements and product components, cannot easily be depicted in an explicit form. It is even more difficult to describe these dependencies as rules. Additionally, these approaches do not take the problem of linguistic fuzziness into consideration.

Although the approaches identified do not solve the problem in question, Category II is promising since it combines the advantages of human and computer. Only approaches where data processing for information is mainly carried by computers seem promising.

6.3 Approach

To develop this approach, the relation between the requirements and the embodiment design was examined. A product is defined as the technical realization of the requirements. In reuse design, the customer requirements determine the variants. Besides the static requirements that exist in all specifications, there are dynamic requirements to be met. In reuse design, these requirements only marginally change from one product variant to another.

If all requirements for defining a product variant are described in the specifications, it presupposes that all connections between the requirements and their embodiment design characteristics are implicitly given in the specifications. Therefore, the specifications of the product variants need to be compared to identify the applicable product variant. The degree of similarity between the specifications of the new order and the pre-existing product variants can be defined using this comparison.

In computer-aided processing, the requirements cannot be processed out of the specifications, since they often exist only as an informal description. Therefore, the requirements need to be transformed into elementary requirements using formularization methods. This minimizes the fuzziness of the informal description of requirements.

To develop a procedure, the approach is divided into three phases:

1. Formularization phase (FP)
2. Preparation phase (PP)
3. Decision phase (DP)

These phases will be examined and the individual steps within them described. The methods necessary for executing the individual steps will also be elaborated. These demands will be used to evaluate the identified methods.

6.3.1 Formularization Phase

In the formularization phase, the informal requirements are transformed into elementary requirements. Methods that use mathematical notations to formularize requirements are not appropriate for practising designers (Fleischmann 2008), which is why the acceptance of such approaches is low. In accordance with the objective, formularization will be made by semi-formal methods. These methods are not purely mathematical as they include linguistic elements. According to Kamsties (Kamsties 2001), using linguistic requirements has three main advantages: universality, flexibility and ease of use.

These methods can be used without further specific knowledge. Because of this, acceptance of the method is expected to be higher. The following demands apply to the semi-formal description of the requirements:

1. The linguistically redundant content of an informal demand needs to be eliminated (compression of information) [F.1].
2. Misleading formulations based on colloquial language need to be reduced [F.2].
3. A demand shall have a defined and uniform structure. In this way, the demands can be processed by a computer [F.3].

6.3.2 Preparation Phase

In the preparation phase, the elementary requirements of the specifications are processed by computer-based methods in such a way that an automatic comparison of specifications is possible.

For an efficient comparison, it is not sufficient to compare individual requirements alone. Their interactions also need to be considered. Information on the interactions is given implicitly in the requirements.

Computer-based, statistical-mathematical methods, which are used to find unknown and non-trivial structures and connections, and are thus used to recognize interactions of data contents, are described as Data-Mining (DM) (Otte et al. 2004). Since these methods are based on statistics, it can be expected that the fuzziness of the requirements can be processed in a useful way. These methods also offer the possibility of visualizing information on the data structure (Ankerst 2001).

As practical experience shows, the number of requirements in a variant design is not consistent. The number of requirements may vary in the specifications. Therefore, the method used for selection needs to be adequate to process such variation in the specifications. The DM method selected needs to meet the following demands:

1. The DM method should have a broad field of application in practice [A.1].
2. The fuzziness has to be processed [A.2].
3. Graphic preparation of the correlation of requirements is essential [A.3].
4. Variations in the requirements have to be considered [A.4].

6.3.3 Decision Phase

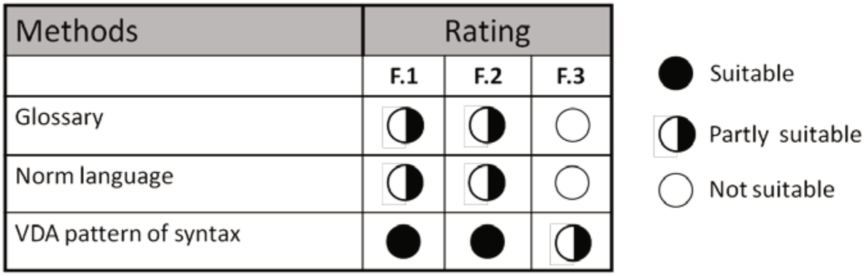
In this phase, the product variant with the highest potential has to be selected. As a result of the processing, a similarity value quantifying the resemblance of the specifications and a visualization of the comparison is needed. This will make it easier for the person in charge to make a decision on the applicable product variant without further support.

6.4 Selecting the Methods for the Three Phases

In this section, the existing approaches that can be used on the concept described in the previous section will be examined. The research will start with the methods of formularization of requirements. The DM methods that fulfil the requirements for use in the concept will then be examined. The methods researched will be evaluated using a three-step evaluation scheme.

6.4.1 Methods for Formalizing the Requirements

"Requirements Engineering" is a field of knowledge which has its roots in computer science and which deals with the systematic process of identifying, documenting and checking the requirements of a technical system (Schulte 2006). Its approaches are investigated for their usability. The methods are evaluated according to the demands stated above, using a three-step evaluation scheme. Figure 6.2 shows the results of the search.



Methods	Rating		
	F.1	**F.2**	**F.3**
Glossary	◐	◐	○
Norm language	◐	◐	○
VDA pattern of syntax	●	●	◐

● Suitable
◐ Partly suitable
○ Not suitable

Fig. 6.2 Evaluation of the methods for formalizing requirements

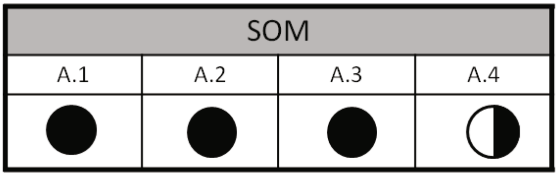
The glossary, as an approach to formalization, is not adequate for the question raised here, since it only assists in defining the terms in a text of requirements. Since there is no clear structure, it is not a stand-alone solution for computer-based processing.

Norm language as such is a Meta language. In common norm language, how to proceed to make a standardized statement is defined. However, the detailed individual steps as well as the methods necessary for making a standardized statement are not part of the description of the norm language. Therefore, there is no clear information included on how grammar and vocabulary can be constricted in a target-oriented way.

The German Automotive Industry Federation (VDA) pattern of syntax is used to describe requirements in the automotive industry. This method splits all original demands into several elementary components. Computer-based processing is possible because of the specified structure. The advantage of this semi-formal mode of description is its practical significance. Higher acceptance in companies can be expected because it is established in industry.

6.4.2 Method Selection for Processing Requirements

Because Otte et al. (Otte et al. 2004) give a good overview of the methods used in practice the first search is based on this publication. The result was that SOM is the only method used for clustering and visualization. The result of the evaluation is shown in figure 6.3. The functionality of SOM is explained in Kohonen (Kohonen 2001).



SOM			
A.1	A.2	A.3	A.4
●	●	●	◑

Fig. 6.3 Evaluation: SOM

6.5 Developing a Procedure Model for Selecting a Product Variant

In this section, the methods selected for describing requirements and automatically processing them are integrated to develop an appropriate procedure model (figure 6.4).

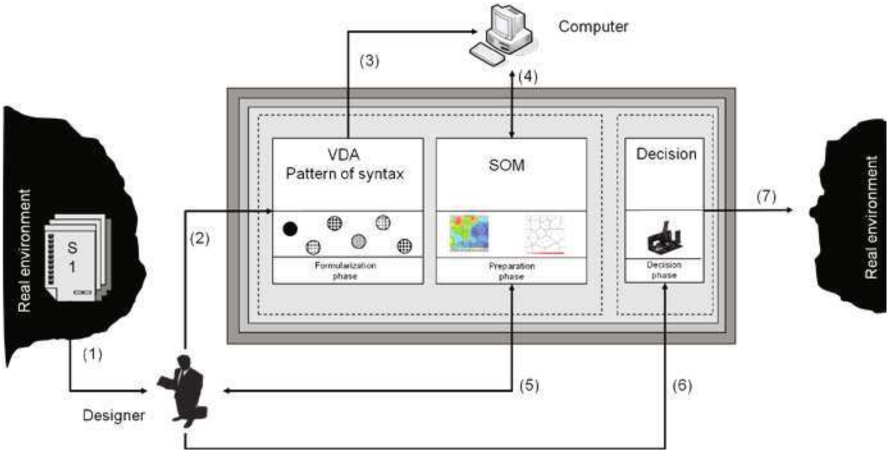


Fig. 6.4 Procedure model

Step (1): The engineer analyzes the specifications. The documented requirements will be added to a list of requirements faultlessly and thus to the model.

This list of requirements will be described in the following as the requirements matrix (RM) to emphasize the multidimensionality of the list.

Step (2): The RM is split into elementary requirements using the VDA pattern of syntax.

Step (3): The quantified requirements are added to a flat table so that they can be processed by the SOM.

Step (4): The SOM is generated and trained using the flat table data. The initialization parameters for the training of SOM process have to be adapted iteratively.

Step (5): The results of the SOM calculation are visualized so that the engineers can effectively check them for plausibility. This step also influences the SOM model, since there might be a need to adapt the initialization parameter of the SOM, depending on the calculated results.

Step (6): Based on the analysis made in Step (5), the engineer can now make a decision.

6.6 Case Study

The procedure for selecting a product variant with the help of SOM is described using the example of a hood lock system (HLS). A medium-sized automotive component supplier validated the approach. Many of the documents used are part of a non-disclosure agreement so it is not possible to provide many details; values and descriptions have been modified. In recent decades, there has been no significant change in the functionality of the HLS. Even if new aspects have to be taken in consideration because of higher safety standards to protect pedestrians, the operating principal has stayed the same. The challenge for the medium-sized automotive component supplier is lowering product costs.

6.6.1 Implementation

The tool SOMine, produced by the company Viscovery®, is used to implement the SOM. SOMine has a user-friendly graphical user interface that is used to define the parameters that constitute the SOM.

To identify an appropriate map that describe the real environment, parameters such as the number of neurons or the neighbouring radius need to be adjusted iteratively. The individual calculations are documented in the software. In this software, the steps executed do not need to be repeated for new calculations. An alternative path with the new parameter will be defined in such cases. This makes it possible to quickly process different calculations.

6.6.2 Analysing the SOM to Make a Decision

First, the neighbours of the product variant selection are identified (figure 6.5). Only the distance to the neighbour solution is analyzed. The analysis shows that the product variants (PV) 07, 12 and 13 have the shortest distance to the new product variant (NPV). For final validation of the result, the requirement attributes that proved the most important factors are visualised to make conclusions for the final selection of the product variants. The three attributes, fracture strength, absolute weight and overall width, are used in the following to explain the procedure. Figure 6.5 depicts these attributes.

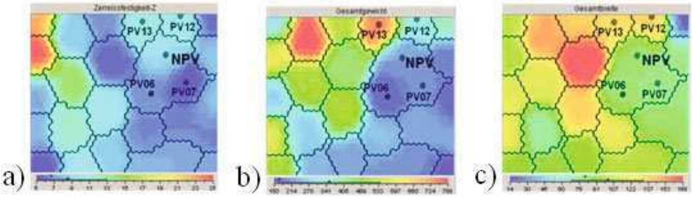


Fig. 6.5 (a) Fracture strength in z-direction, (b) absolute weight, (c) overall width

The visualization of the attribute "fracture strength-z" shows that the product variants 12 and 13 result in very similar values to the ones required for the new application. Therefore, a choice must be made. Comparison with the attribute "absolute weight" shows that the weight of variant PV13 is higher than the new product variant. The variants PV06 and PV07 have a similar lower weight, as required. For overall width, the product variants PV06 and PV07 are preferred. If it is not possible to use a larger HLS because of the available space, and if the requested higher fracture strength is a fixed requirement, and if no other factors are regarded as equally important, none of the product variants identified so far can be used. In this case, none of the discussed variants is appropriate for the design task. Consequently, the product variants in the upper-left of the map have to be analyzed.

For a final ranking, the test values of the product variant were also considered. The test values show that, in most cases, the product variant overachieved the requirement. Using this knowledge, a final decision was made. PV06 was the most successful variant in this project, followed by variants PV07, PV12 and PV13.

The procedure shows that it is not possible to get an unambiguous and automatic decision. Because of this, a human decision-maker has to make a decision based on all available pieces of information.

6.7 Summary

The main outcome of this research is the fundamental findings on appropriate task allocation between humans and computers in decision-making processes in product development and design. The computer-based method SOM can be used to visualise the relationship of the data in a comprehensible way. Humans can combine their own experience with the information from the visualisation to make a better decision.

This may uncover optimization potential in many computer-based applications in today's expert systems. Beyond the field of product development, other applications where the human mind is overwhelmed by the amount of available data might benefit from the approach outlined of using computers for data preparation.

The basic prerequisite for using SOM effectively is the availability of sufficient data. While this is not the case for all applications in product development, there are industries that can utilize substantial amounts of relevant data from former projects that affect a current project. Even if the SOM analysis does not produce an immediate solution to a design problem, it can support the decision-making process by graphically depicting available options that may have been overlooked. Critical analysis of the validity of the underlying data and the SOM results is crucial to the success of the approach.

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Chapter 7

Increasing Effectiveness and Efficiency of Product Development - A Challenge for Design Methodologies and Knowledge Management

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Abstract Information transfer and decision making play dominant roles in the product development process. Information has to be retrieved, processed and outputted permanently. Thus, knowledge is generated and required to design this process effectively and efficiently, including making the right decisions. Therefore, supporting the product development process is a major task of design methodologies, knowledge management and tools. The future of Design Methodology has to be orientated around prospective product development. The present state of and challenges in product development are briefly described in this paper to realize future objectives for product development. Engineering Design Methodology's general contribution and the Institute for Engineering Design and Industrial Design (IKTD)'s detailed schemes for achieving these objectives are depicted.

7.1 Present State of and Challenges in Product Development

The way designers work in product development has changed tremendously in recent decades and will continue to do. These changes are in some part caused by enormously improved IT support that allows new and enhanced methods for calculation and simulation, product representation using CAD and PDM/PLM systems, new communicative devices, global networks, and new materials and technologies (Birkhofer et al. 2009). This evolution correlates with greater competition in the global market. The production and product development within globally active companies is increasingly spread all over the world. Collaboration across different time zones and cultures makes development work much more difficult.

Standardized products cannot serve the sophisticated global market; it needs special products for special markets and individual customers. The trend of product individualization has led to an increasing number of customer-tailored products, often combined with big challenges in complexity management. High-tech products for ripe markets do not necessarily fit to emerging markets. Designers

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have to consider local circumstances, infrastructure and the requirements of the target market. This means, for example, that an increasing number of international and national standards and guidelines must be taken into account.

To be successful, globally acting companies and small to medium-sized enterprises need lean and reliable product development processes. However, especially in small companies, this process is often ill defined. If it is well defined, however, in many cases it is not consequently implemented and accomplished, regardless of the size of the company. The danger posed by excessive regulation and bureaucracy should not be underestimated either.

Besides the quality of the product development process, the performance of the applied design methods and tools is decisive in achieving good results. Although Engineering Design Methodology became part of design education more than 40 years ago (and is praised by the academic community for its benefits) application in industry is moderate. Methods are often perceived as too complex and time-consuming. The results of some methods can vary, because they depend on the competence and experience of the users. This dependency is a problem for a stringent development process. An uncritical application of the methods can lead to aberrations or misinterpretations. Integration of the methods and their IT support is improvable. Since intensively validating newly developed methods in industrial practice is problematic, this could be one of the reasons for the perceived low uptake.

The performance of the IT tools supporting the development process has improved immensely. Although these powerful tools are very helpful to designers, they also represent a big challenge for the users due to their high complexity and multiple user interfaces. In spite of good visualization tools, users often cannot appraise the validity and the plausibility of calculations or simulations.

Lastly, the product developers are the determining factor. Above all, their knowledge, expertise, competencies and skills are decisive in creating excellent products. For this reason, it is extremely important to have the "right" knowledge in a company, to expand, preserve and transfer it to future generations and to make it easily accessible to everybody who needs it. Considering the ongoing explosion in knowledge, the significance of knowledge management will increase.

The main success factors for products – quality, cost and time – have become more and more important and are the same success factors in product development. Effectiveness and efficiency of product development highly influence the success of enterprises.

7.2 Objectives for Product Development in the Future

The deficiencies and challenges in current practice lead to these objectives for product development in the future:

Product development has to become faster. Globalization has increased competitive pressure on all companies, and "time to market" has become an essential success factor. Focusing on the most promising projects and taking the "right" decisions is necessary to avoid development loops to accelerate processes.

Product development has to become "better" in terms of quality and reliability of the development results. Increasing complexity and individualization of technical products and systems along with shortened development times holds the risk of increasing failures, as, for example, in the automotive industry in the past. Thus, it is not only necessary to do "the right things", but also to do "things right". Product development has to be based on lean and reliable processes to become more efficient and effective.

7.3 The Contribution of Engineering Design Methodology and Knowledge Management to Achieving the Objectives

In the future, Engineering Design Methodology and knowledge management should contribute greatly to achieving these objectives, as excellent tools support them. To increase the use of design methodologies in industry, it is necessary that the methodologies fulfil the following requirements.

7.3.1 Requirements on Engineering Design Methodologies

Engineering design methodologies are an approach for solving a task or a problem. They refer to appropriate methods and tools. From a designer's point of view, methodologies are prescriptive. Thus, a methodology may be considered as a directive pointing towards the possible best-fit methods or tools within a science or art for coping with a task or problem.

As in Blessing et al. (Blessing et al. 1998), the "aim of engineering design research is to support industry by developing knowledge, methods, and tools which can improve the chances of producing a successful product". If and how an engineering design methodology can provide this support in reality has to be assessed using appropriate criteria.

A methodology has five distinct aspects: Normativity, didactics, uncertainty, competitiveness, and match & limit. These aspects can be further split into 19 requirements on engineering design methodologies, which fall into eight groups, as shown in Table 7.1.

Table 7.1 Aspects of a methodology, description of related groups, and grouped requirements on engineering design methodologies (Keller and Binz 2009)

Aspect	Group Description	Grouped requirements
Normativity	*Revisability* by appropriate and accepted means	Validation Verification
	Scientific Soundness by backing up the hypotheses of a methodology	Objectivity Reliability Validity
Didactics	*Comprehensibility*	Comprehensibility Repeatability Learnability Applicability
Uncertainty	Providing a s*tructure* for complex tasks and problems and *compatibility* with different environments	Handling complexity Problem solving cycle Structuring Compatibility
	Providing *flexibility* for the designer using degrees of freedom when applying a methodology	Flexibility
Competitiveness	*Practical relevance* and *competitiveness* by satisfying a need for a methodology	Innovativeness Competitiveness
	Usefulness	Effectiveness Efficiency
Match & Limit	*Problem specificity* allowing links between an assignment and a matching methodology, and defining the application limits of a methodology	Problem specificity

This framework of requirements is used at IKTD as a guideline for assessing, choosing and developing engineering design methodologies and support.

7.3.2 IKTD's Approach

Methodical product development research activities at IKTD are geared to "Doing the right things right!"; developing or enhancing methodologies and tools to improve effectiveness and efficiency in product development. To select "the right things", e.g. project ideas, evaluation methods can be useful and are therefore investigated. For "doing things right", specialised and methodical knowledge is essential. In light of the recent knowledge explosion, good knowledge management will become a decisive success factor in global competition. Therefore, the aim is to support designers with the right knowledge, in the right place, and in the right way. Four research projects are briefly described to illustrate IKTD's approach to achieving this.

7.3.2.1 Evaluation of Innovative Product Ideas

To meet current and future challenges, such as globalisation, saturated markets, shorter product life cycles and greater pricing competitiveness, successful innovations are of central importance to all kinds of companies. New, successful products are the best way to master this increasing competitive pressure. It will only be possible to maintain a high standard of living in industrialised countries if companies succeed in developing and distributing innovative products (Meffert et al. 2008).

However, being innovative by developing new, successful products is not easy for companies. The majority of new product ideas will end in failure. Many product ideas are rejected during the product development process because they do not appear promising. Even if a new product idea has been developed and introduced into a market, there is still a great risk of failure.

Due to the vast number of ideas necessary for the development of innovations, combined with emerging skill shortages that limit company resources, it is reasonable to put the focus on increased effectiveness first. Only by concentrating on "the right things", selecting only the most promising product ideas for further development, is it possible to use the available resources effectively. Therefore, idea evaluation and selection is an important aspect of future design methodology. The aim of this research project is the creation of a usable and well-developed evaluation method.

Most of the requirements on Engineering Design Methodologies, as cited in Section 7.3.1, can be broken down and used to create an evaluation method for assessing innovative product ideas. However, not all of the stated requirements can be met by existing evaluation methods. Comprehensibility (Table 7.1) particularly has to be improved. Existing methods are often too complex and time consuming. Only a few of them are used in corporate practice because of their methodological deficits (Gausemeier et al. 2000). Therefore, it is a special challenge to researchers to improve existing evaluation methods so that product ideas can be evaluated and selected more quickly and efficiently. The time and costs spent on evaluation have to be reduced. The quality and reliability of the evaluation results also have to be improved.

To examine existing methods in detail and to identify their strengths and weaknesses, all relevant aspects of an evaluation have to be assessed. The range of criteria used to evaluate product ideas is an important aspect. Initial analysis shows that there are four factors essential for product success: product advantage, customer orientation, market-related factors and synergy. These factors are dependent on the type of innovation that is evaluated. For example, factors crucial for radical innovations are different to those for incremental innovations (Messerle et al.

2010). Whether this is applicable to more general aspects of the product development process needs to be examined. It might be possible to achieve an increase in the integration of design methodologies in corporate practice by adapting methods and methodologies to particular circumstances, for example, to different types of innovation.

After selecting the most promising product ideas, a high-quality product development process has to be carried out. Thus, another area of focus is increasing the efficiency of the product development process. Several aspects of this research are presented in the following sections.

7.3.2.2 Systematic Design of Hybrid Intelligent Design Elements (HIKE)

In the future, new design elements will be required that provide new, consolidated and more significant functionalities and properties. This holds for any discipline with highly dynamic product development cycles, such as mechanical, automotive, aeronautical and civil engineering. These requirements arise both from social and market driven demands, such as integrated extended functionality, energy consumption, lightweight construction, recyclability, and added technical value in general. Hence, basic design elements with extensive, integrated intelligence are needed for progressive and high value integrated products.

Hybrid intelligent design elements (HIKE) are one way of meeting these objectives. HIKE are being developed by a research group funded by the German Research Foundation (DFG). HIKE combine the functionalities of sensors, actuators, and/or mechanical structures. In conjunction with an (integrated) intelligence, they enable purposeful adaption of the behaviour of a technical system. Thus, changing influencing factors of the surroundings of such a system (such as load changes) can be detected, reacted upon, and, for example, peak stresses can be compensated for.

HIKE use “smart materials” with novel properties. The interdisciplinary development of HIKE, and systems using HIKE, is taking place in close collaboration with mechatronics (comprising discrete constructional elements) and adaptronics (comprising integrated constructional elements). For example, electroluminescent yarns emit light in response to conducting an electric current, changing their properties because of mechanical strain, and, thus, may change the colour of the emitted light. Integrating them into technical textiles (providing the mechanical structure) allows the integration of sensor and display functions. Connection to a control unit using the sensor information for monitoring the state of the mechanical structure is easily possible. Figure 7.1 is a generalized description of the composition of HIKE, consisting of a mechanical structure, a sensor, and/or an actuator.

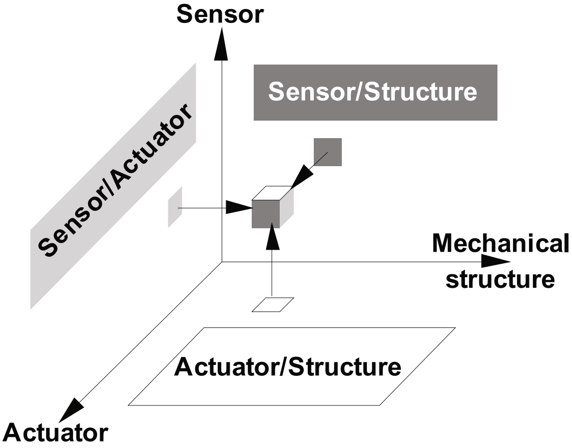

Fig. 7.1 General composition of a hybrid intelligent design element (HIKE), consisting of a functional combination of a sensor, an actuator, and a mechanical structure

Developing these parts and implementing them into a common prototypical system raises several issues, especially from an engineering design research point of view:

- How to develop and design HIKE: to achieve the integrated abilities demanded of HIKE, interfaces have to be considered and established during the developing stage of HIKE. Hence, an adapted process and support is required.
- How to design *with* HIKE: when designing with HIKE, properties and characteristics have to be provided in an interdisciplinary and understandable way. A relationship between HIKE and current knowledge on design processes, methodologies and technical systems has to be established.

During the designing of and with HIKE, developers and designers need information on HIKE, which can be computer-based:

- Function and general effect
- working principle, structural characteristics and properties
- control properties and intelligence
- structural shapes
- design and application guidelines (Design for HIKE / DfX / DtX)
- methods, tools, and utilities.

A Wiki is currently being developed that provides a structure based on this list. This tool is appropriate for supporting the locally distributed and interdisciplinary collaboration with regard to the exchange of information and knowledge. It permits the integration of all relevant information and the interactive extension and upgrading of common knowledge. Information is useful if it can be linked with existing cognitive chunks and used to expand them. Thus, the Wiki integrates the common design elements as well. The process of developing of and designing *with* HIKE is extensively affected by the need for interdisciplinary work. The fundamental requirements on a methodology that supports this process are efficiency, learnability, comprehensibility, reliability, and objectivity.

7.3.2.3 Proactive Support of Product Development Processes with Multi-Agent Systems (ProKon)

Another way of meeting the challenges of product development (PD) is using knowledge-based systems (KBS). The overall goal of KBS in PD is supporting design engineers (Studer et al. 1998). In a collaborative project called ProKon (Proactive support of product development processes with multi-agent systems), funded by the DFG, an agent-based design support system (ABDS) was developed. Compared to other KBS, agent-based systems have the advantage that they can work in a complex environment, provide an active behaviour and are very flexible in modularity (Göhner et al. 2004). In the context of PD, a complex environment implies a complex and distributed problem with many constraints and a huge amount of knowledge to be processed. Based on this, the overall challenge of this project is to combine product development with neighbouring fields of interest: multi-agent systems, knowledge engineering, engineering design knowledge and theory of CAD systems.

There are several requirements that the system should fulfil. First, the ABDS has to monitor the CAD model to work autonomously without activation by the engineer. This means that the system tracks every step of designing (e.g. variation of a length of the shaft). If problems in the CAD model are detected (variation leads to inconsistent design of existing standards), the system searches for solutions (variation of geometry, material or type of machine element/type of connection) and offers a selection of the found solutions to the engineer. A certain flexibility is required to extend the system by further knowledge, e.g. new technologies or standards.

To fulfil these requirements, two classes of agents are involved. CAD agents are responsible for the interface of the CAD system and retrieving information on parts, assemblies and connections. The management agents represent the second class. This class consists of three sub-classes: the management agent, several aspect agents and a number of specialist agents. This second class is responsible for checking the consistency of the CAD model, finding solutions for the existing inconsistency and executing them within the CAD system (Kratzer et al. 2010). The overall structure of the ABDS is shown in figure 7.2.

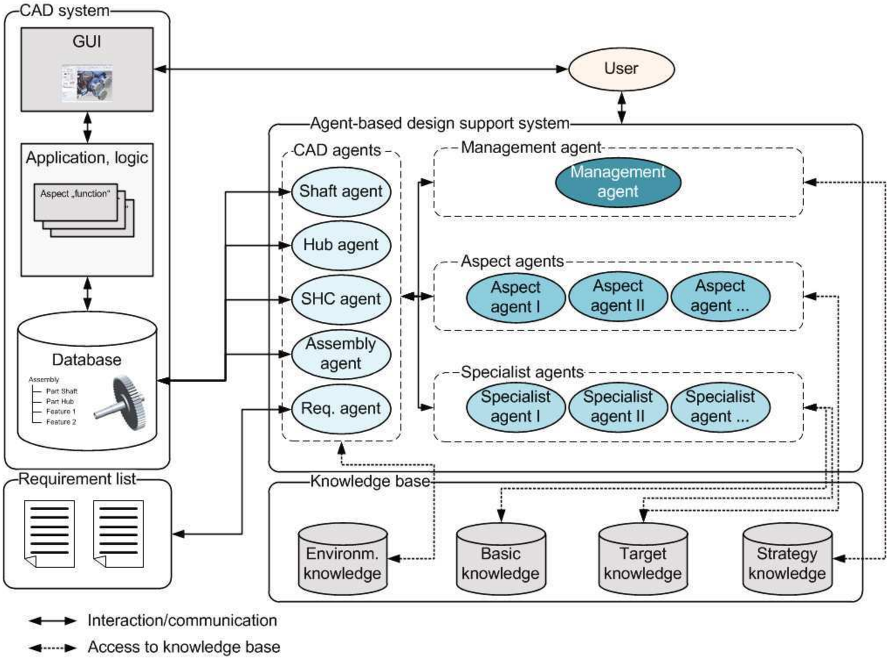

Fig. 7.2 Overall structure of the agent-based design support system (abbreviations: SHC = shaft-hub connection, Req. = Requirement, Environm. = Environmental, GUI = Graphic User Interface)

Currently, ABDS can be used to check the consistency of a simple application scenario (shaft-hub connection) then finding solutions and executing them. The interface between the ABDS and the CAD system (Pro/Engineer) is defined and developed. In a second project phase, a knowledge integration system has to be developed to integrate engineering design knowledge in a user-defined and user-friendly way. A crucial aspect of this project is defining the “right” knowledge to be integrated. What is the right knowledge and where should it be applied? This question and others will be answered in the next section.

7.3.2.4 Evaluation of Product Development Knowledge (PDK^{bench})

Resource knowledge becomes an increasingly important factor in production and, in particular, in the outcome of the product development process (PDP). Therefore, it is important for companies to ensure that the correct knowledge is available at the right time, in the right place, and in an adequate form. According to Steinhübel (Steinhübel 2006), “it is necessary to firstly identify the knowledge that is essential for market success - this is the value adding knowledge - then to make it accessible, available and to enhance it”. This project must develop a method to measure product development knowledge (PDK).

When using measuring systems, the properties of the quantity to be measured have to be identified. Based on this, knowledge has to be instrumentalised to improve competitiveness. This requires analysis of the knowledge and its interrelation with and influence on competitiveness.

Roth et al. (Roth et al. 2010) introduced terms for knowledge within product development. This approach defines knowledge by its:

- *type*: the specific/thematic domain represented by the knowledge (e.g. specialised or methodical knowledge)
- *character*: characteristic properties (e.g. implicit or explicit)
- *form*: occurrence of knowledge (e.g. text or figure)
- *location*: origin of knowledge (e.g. person or database)
- *quality*: “correctness” of knowledge (the meaning of “correctness” is not discussed in this paper).

Beyond this, an essential part of the method to be developed is knowing the general structure of knowledge required. To achieve this goal, IKTD developed a structuring model (Roth et al. 2010), as shown in figure 7.3 (based on empirical results in an academic environment – analysis within industry is in progress). In contrast to former structuring models, this model analyses which knowledge is necessary in which phase of the PDP. According to Pahl and Beitz (Pahl and Beitz 2006), the PDP can be divided into four phases. In each of these phases, specific product development knowledge is required and generated. The method must deal with these phases to permit evaluation of the existing knowledge. Therefore, the structuring model developed subdivides relevant knowledge types into two categories (administration and implementation) then demonstrates their interconnectedness, relations and significance within the PDP. However, the designers’ needs must correlate strongly with their activities. A CAE engineer will have different needs to a materials science engineer or an expert in mechanics of materials.

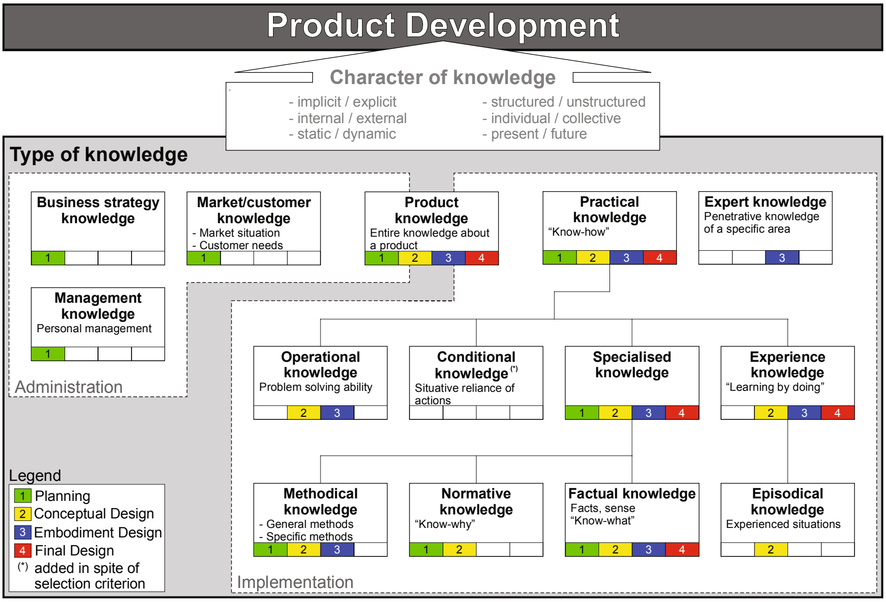

Fig. 7.3 Theoretical model of the general structure of knowledge

It is important to know which knowledge is required within the PDP; coping with the ever-increasing amount of knowledge in society is only possible in this way. The IKTD plans to contribute to the purposeful development of this knowledge base by developing a method for evaluating knowledge within the PDP.

7.4 Conclusion and Outlook

Effective and efficient product development, in combination with employee knowledge, is increasingly becoming a decisive factor in the tough global market. Thus, it is a major challenge for engineering design research to develop new and improve existing methods and tools to support companies. The scope of research should not focus overly on design methodologies, but should also consider aspects of knowledge management in product development. The research projects of the IKTD show the potential methods to bridge the gap between these domains. This contribution could mean that design methodologies will be applied more often and more successfully in future.

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Chapter 8
Design Theory and Methodology – Contributions to the Computer Support of Product Development/Design Processes

C. Weber[1]

Abstract Based on a conference paper published by Weber and Birkhofer (Weber and Birkhofer 2007) on requirements of Design Theory and Methodology (DTM), this article investigates DTM's contributions to progression, systematisation and application of computer methods/tools for product development/design processes. Using the CPM/ PDD approach ("Characteristics-Properties Modelling", "Property-Driven Development/Design"), investigations of computer-based analysis and synthesis methods/tools, product models/modelling and controlling the development/design process are presented.

8.1 Introduction

Birkhofer and Weber's conference paper "Today's Requirements on Engineering Design Science" (Weber and Birkhofer 2007) was inspired by Birkhofer's great efforts in consolidating and modernising Design Science (Birkhofer 2004, Birkhofer 2006), many formal and informal discussions on the topic, and a jointly organised workshop "Engineering Design Science – Consolidation and Perspectives" at the DESIGN 2006 conference.

In Weber and Birkhofer (Weber and Birkhofer 2007), four main groups of stakeholders who have expectations and requirements of Design Theory and Methodology (or "Design Science") were identified: Scientists, designers in practice, students (including PhD candidates), and tool/software developers. This paper focuses on developers:

- What are the expectations and requirements of Design Theory and Methodology (DTM) in terms of computer support of development/design processes?
- What and how can DTM contribute to the progression, systematisation and application of computer methods/tools for product development/design?

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8.2 Requirements of Design Theory and Methodology

Weber and Birkhofer’s (Weber and Birkhofer 2007) core findings that relate to computer support of product development/design processes were, in brief, that promotion of DTM took place in roughly the same period as the evolution of computer models, methods and tools supporting product development/design (CAx tools). However, despite some very early attempts (e.g. Seifert 1986), DTM is not integral to the definition and development of (CAx) tools. DTM should provide a sound formalisation base for the progression, systematisation and application of computer methods and tools. This requirement has two sides – supporting **designs** (the products and product models) and **designing** (the processes and process models).

Weber and Birkhofer (Weber and Birkhofer 2007) ends with a list of computer support requirements of DTM, which is summarised in Table 8.1.

Table 8.1 Computer support’s Requirements of Design Theory and Methodology (Weber and Birkhofer 2007)

Developing a coherent description and prescription:	
… of products	… of development/design processes:
Product properties and their relations	General process framework
Cope with multitude of properties	Specific/“situated” processes
Multi-domain approach	Assigning methods/tools to processes
Formalisation	Formalisation
Modular product models	Modular process models (workbenches)
Development and application of new methods/tools for product modelling	Development and application of new methods/tools for process support
Acceptance of methods and tools	Acceptance of methods and tools
Relation to business goals	Work distribution, collaboration
Integration into existing environments	Integration into existing environments

The desire to enhance and extend computer support of product development/ design processes is an important reason why product and process descriptions have to be formalised more rigorously than in the past.

8.3 Theoretical Base

In the last couple of years, a way of modelling products and product development/design processes has been developed: “Characteristics-Properties Modelling” (CPM) and “Property-Driven Development/Design” (PDD). Characteristics-Properties Modelling (CPM) is the **product** modelling side; Property-Driven Development/Design (PDD) explains the **process**.

The CPM/PDD approach was heavily inspired by work on new computer tools in the 1990s, and has turned out to be a useful concept for systemising the development and application of computer support in product development/design. Therefore, it is used as the base for further deliberations and is explained briefly in this section.

CPM/PDD has been explained in more detail in several earlier publications (Weber et al. 2003, Weber 2005, Weber 2007, Weber 2008, Vajna et al. 2009).

The CPM/PDD approach is based on the distinction between the characteristics (in German: “*Merkmale*”) and properties (“*Eigenschaften*”) of a product:

- C**haracteristics** (**C**$_i$) are made up of the structure, shape, dimensions, materials and surfaces of a product (“*Struktur und Gestalt*”, “*Beschaffenheit*”). They can be directly influenced or determined by the development engineer/designer.
- P**roperties** (**P**$_j$) describe the product’s behaviour, e.g. function, weight, safety and reliability, aesthetic properties, but also things like manufacturability, assemblability, testability, environmental friendliness, and cost. They cannot be directly influenced by the developer/designer.

The characteristics are very similar to Hubka & Eder’s (Hubka and Eder 1996) “internal properties” and what Suh (Suh 1990) calls “design parameters”. The properties, as introduced here, are related to the “external properties”, as defined by Hubka & Eder (Hubka and Eder 1996), and “functional requirements”, according to Suh (Suh 1990).

For reasons discussed in other papers, Andreasen’s (1980) nomenclature “characteristics/properties” is used here.

The discussion about product properties (and characteristics), and appropriate terminology has been led by Birkhofer, Andreasen, Eder, Weber and many others in recent years. Birkhofer proposed a new terminology in (Wäldele and Birkhofer 2008, Birkhofer and Wäldele 2009): What is “characteristics” here (or “internal properties”, according to Hubka and Eder) could be called “independent properties”. “Properties”, as used here (or “external properties”, according to Hubka and Eder), becomes “dependent properties”.

Characteristics and properties are two different concepts for describing products and their behaviour, respectively. As mentioned previously, the concepts have been used in DTM for a long time. The only new aspect of CPM/PDD is that this duality is in the **centre** of modelling products and product development/design processes.

To handle characteristics and properties – literally thousands of them in complex products – and to keep track of them in the development process they have to be structured. Figure 8.1 shows the basic concept, as discussed in CPM/PDD:

- On the left, a proposition for the (hierarchical) structuring of characteristics is given, following the parts' structure (or tree) of a product. It complies with standard practice, and links considerations to the data structures of CAx systems.
- On the right, a proposition for the top-level headings of structuring properties is presented, based on life-cycle criteria, and reflecting frequently discussed issues in product development/design.

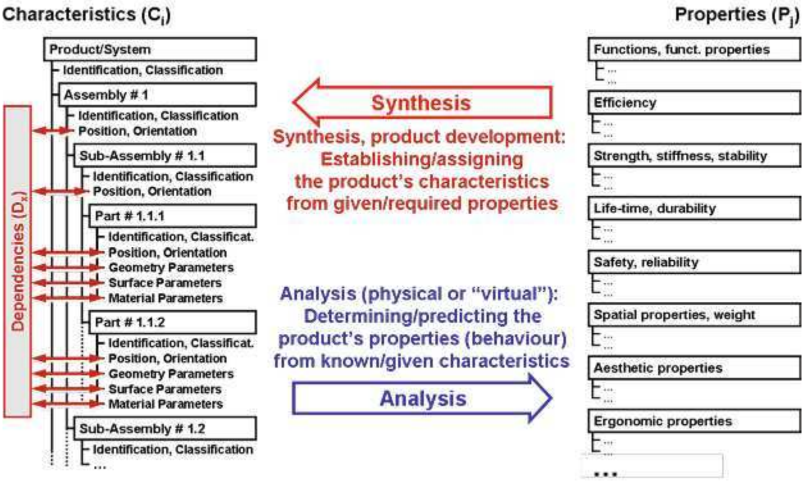


Fig. 8.1 Characteristics and properties, and their two main relationships

On the characteristics (left) side of figure 8.1, an additional block is drawn that represents dependencies (**D$_x$**) between characteristics. Development engineers and designers are familiar with these types of dependencies, e.g. geometric or spatial dependencies, as well as those concerning fits, surface and material pairings, even conditions of existence. Geometric and spatial dependencies can now be captured and administered by parametric CAD or PDM systems. Figure 8.1 also shows the two main relationships between characteristics and properties:

- **Analysis:** Based on known/given characteristics (structural parameters, design parameters) of a product, its properties can be determined (and therefore, its behaviour), or – if the product does not yet exist – predicted. In principle, analyses can be carried out using experiments (using a physical model/mock-up or a prototype) or virtually (by calculation and/or using digital simulation tools).
- **Synthesis:** Based on given, i.e. required, properties, the product's characteristics are established and appropriate values assigned. Synthesis is the main ac-

tivity in product development: The requirements list is, in principle, a list of required properties – the task of the development engineer/designer is to find appropriate solutions, i.e. an appropriate set of characteristics that meet the requirements to the customer's satisfaction.

In the CPM/PDD approach, analysis and synthesis, as the two main relationships between characteristics and properties, are modelled in more detail, following a network-like structure. Figure 8.2 and figure 8.3 show the two basic models for analysis and synthesis, respectively. For reasons of simplification, a simple list (or vector) structure is displayed as an idealisation for both characteristics (**C_i**) and properties (**P_j**, **PR_j**, respectively).

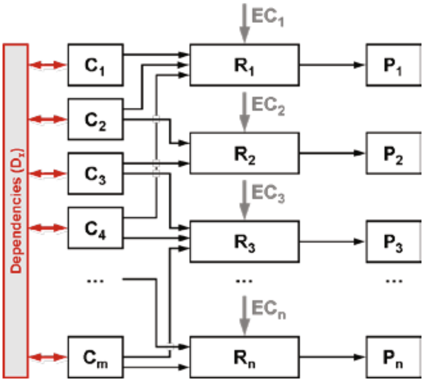


Fig. 8.2 Basic model of analysis

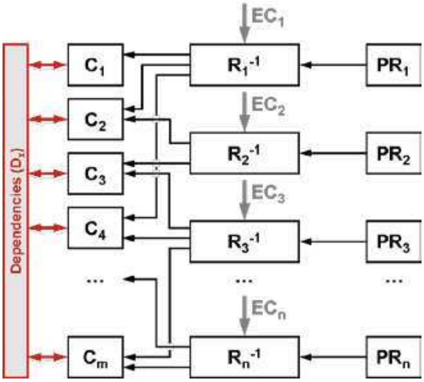


Fig. 8.3 Basic model of synthesis

Table 8.2 Key for figures 8.2, 8.3 and others

C_i:	Characteristics ("*Merkmale*")	**R_j, R_j^{-1}:**	Relations between characteristics and properties
P_j:	Properties ("*Eigenschaften*")		
PR_j:	Required Properties	**D_x:**	Dependencies ("constraints") between characteristics
EC_j:	External conditions		

During product development/design, the finished product does not yet exist. Therefore, the "relation boxes" (**R_j**, **R_j^{-1}**) have to be represented by appropriate methods and tools; these can be based on physical or non-physical, for example, digital models.

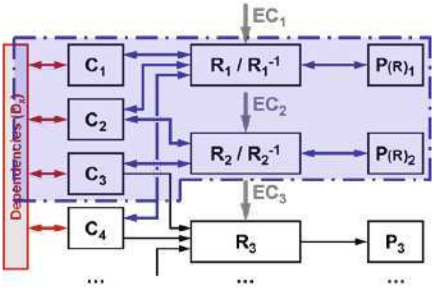


Fig. 8.4 Schematic representation of a solution pattern/element

An important issue in practical development/design processes, as well as in their computer support, is the (re-) use of solution patterns/elements. From the perspective of the CPM/PDD approach, a solution pattern is an aggregation of characteristics (**C**$_i$) and properties (**P**$_j$) with known relations (**R**$_j$) between the two (figure 8.4).

Once a solution pattern/element is known, it can be used in both directions, i.e. for analysis and synthesis purposes.

The term "solution pattern/element" addresses function-based solution patterns, which have been investigated in DTM for a long time (e.g. Roth 1982, VDI 2222.2). But it can also be extended to other relevant properties, such as manufacturing, assembly, strength, safety-related patterns, etc. Practical product development/design, to a considerable extent, is a process of superimposing proven solution patterns/elements from different fields, hopefully causing minimal conflicts on the characteristics side.

Investigations so far have mainly addressed product-modelling (CPM). A process model (PDD) develops from CPM when the evolution of characteristics and properties is followed over time: Product development/design is a process consisting of cycles that implies the following steps (figure 8.5):

1. **Synthesis:** Starting from required properties (**PR**$_j$), characteristics (**C**$_i$) of the future solution are established. This is often achieved by adopting partial solutions from previous designs (solution patterns/elements; Fig. 4).
2. **Analysis:** In this step, the current properties (**P**$_j$, as-is properties) of the solution state are analysed, based on the characteristics established so far. In this step, the properties that went into the preceding synthesis step are analysed, as well as all other relevant properties (as far as is possible at this time).
3. **Determining individual deviations:** Next, the results of the analysis (as-is properties) are compared with the required properties, the deviations between the two (**ΔP**$_j$) representing the shortcomings of the current design.
4. **Overall evaluation:** The development engineer/designer now has to run an overall evaluation; extracting the main problems and deciding how to proceed, that is, pick out the property/properties to be addressed next and select appropriate methods and tools for the subsequent synthesis-analysis-evaluation cycle.

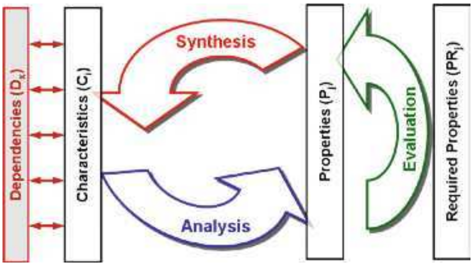


Fig. 8.5 Scheme of the product development/ design process consisting of cycles of synthesis–analysis-evaluation steps

From one cycle to the next, because of each synthesis step, more and more characteristics are established and their values assigned ("detailing" the structural description of the solution). The analysis steps of all cycles all deal with the same properties repeatedly – but with a modified and/or extended set of characteristics, thus creating increasingly precise information about the product's properties/behaviour. Consequently, the analysis methods and tools have to switch from being rough to increasingly exact and detailed as the process progresses.

The product development process as a whole is controlled or driven by the evaluation of the gap between required and as-is properties at the end of each cycle. The process terminates if and when:

- all characteristics needed for manufacturing and assembly of the product are established and assigned ($\mathbf{C_i}$)
- all (relevant) properties can be determined/predicted ($\mathbf{P_j}$)
- with sufficient certainty and accuracy
- all determined/predicted properties are close enough to the required properties, i.e. the "deviation vector" becomes minimal ($\underline{\mathbf{\Delta P}}_\mathbf{j} \rightarrow \underline{\mathbf{0}}$).

8.4 Computer Support in Product Development/Design

In this section, some conclusions on the progression, systematisation and application of computer methods and tools for the product development/design process will be derived. The investigation takes the CPM/PDD approach (Section 3) as a starting point, then reasons from there to useful computer methods and tools, and their roles in the process (not the other way around, as is often the case: starting from existing methods/tools and fitting the process).

In principle, computer methods/tools can support the following activities: Analysis and synthesis steps, documenting development/design results (current/intermediate, final results), and controlling the development/design process.

Analysis and Synthesis

Computer-based analysis methods/tools realise the “relation boxes” ($\mathbf{R}_j$) shown in figure 8.2 within the process in order to predict the properties of the product being developed/designed. Computer-based analysis corresponds to the term “CAE” (computer-aided engineering) in IT language.

“Conventional” methods of analysis, and viable alternatives, are estimations, experience, physical tests/experiments, using past experiences in the form of tables and diagrams, and conventional calculations. Computer support can be more objective (compared to estimations and experience), precise (compared to conventional calculations), detailed (compared to experiments), and less time and cost consuming (compared to experiments). Therefore, the importance of using computer support for analysis is increasing, clearly and justifiably.

Using the CPM/PDD approach, the following is deduced:

- Analysis methods/tools must be assigned specifically to product properties to be analysed. As with different types of products, different sets of properties are relevant, a huge number of special analysis tools is needed to cover all needs. Contrary to this need, software developers tend to cover only the most general classes of properties (e.g. delivering FEM systems, analysing mechanical properties which are somehow relevant in most [mechanical] products). This is understandable for economic reasons (of the software supplier); it becomes a problem, however, if a selection of quite general systems is marketed as a “fit-for-all” solution, as can be increasingly observed in today’s market. The challenge here is how to provide useful and economically viable computer support for the large variety of properties in many industries and companies.
- Within one class of properties, several methods/tools are needed, according to the state of the development/design process: The CPM/PDD approach demonstrates that all analysis steps consider the same set of properties. However, in the “early phases”, a small number of characteristics are already assigned; they require methods/tools that can deliver statements about properties without being fed many details (and which in future might remain quite “conventional” without losing anything). “Late phases” are defined by much more detailed descriptions of the solution (many characteristics assigned); only then will elaborate tools and methods be applicable. The value of comprehensive, numerical tools is **not** in replacing “conventional” tools (they keep their strengths in early phases), it lies in making the late phases more precise, more detailed, less time and cost consuming, etc.

When using computer methods/tools for analysis (as well as synthesis), an additional influence factor has to be considered: The validity of a statement about a property is not only dependent on the characteristics ($\mathbf{C}_i$) and the assumed external conditions ($\mathbf{EC}_j$), but also on the modelling conditions ($\mathbf{MC}_j$) (figure 8.6). They must be clearly defined and stated (by providers and users of the computer method/tool) so that the use and results of the respective tool are not compromised. For example, results of an FEM analysis can only be interpreted if the element types, meshing, and boundary conditions implied are known – all of these having nothing to do with the real problem, only with the "conditioning" of the problem for the computer.

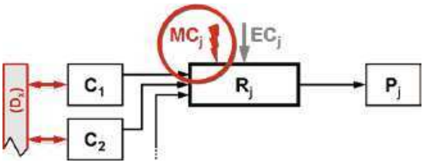


Fig. 8.6 When using a computer method/tool, the modelling conditions (**MC_j**) have to be known

Computer-based analysis methods/tools utilise many different IT concepts: Physical models turned into mathematical models and numerically solved (the most common case), as well as rule-based strategies, fuzzy logic, semantic or neural networks, case-based reasoning, etc.

For computer-based synthesis methods/tools, ways to realise the "inverted relation boxes" (**R_j^{-1}**) need to be found, as shown in figure 8.3. It is doubtful whether a computer system can ever be expected to develop/design a new product "from scratch", i.e. without reference to previous solutions or solution elements. It may even be wrong to foster expectations: Computers are perfect for "number-crunching", i.e. analysis purposes; for creativity, i.e. synthesis purposes, humans are much better.

However, two concepts of supporting synthesis are known and have been utilised successfully (the first for decades):

- Store solution patterns in computers: As in Section 8.3 (figure 8.4), solution patterns can be used for both analysis and synthesis. Typical examples are CAD features and feature libraries (Weber 1996, VDI 2218), which can be part of feature recognition (analysis) and feature-based design (synthesis). Much older examples are variant programmes/modules for CAD. Quite recent extensions come under the heading "Knowledge-Based Engineering" (KBE). The still very static nature of the concepts mentioned poses a challenge still to be tackled: Usually they can address only one particular phase or cycle of the product development/design process, and cannot follow the dynamic growth and change of product characteristics and knowledge about product properties.
- Optimisation methods/tools imitate synthesis-analysis-evaluation cycles that, according to the CPM/PDD approach, are the main explanation of the product development/design process as a whole (Section 8.3, Figure 8.5). An example already commercially available is software systems for structural optimisation. However, they need a start solution first: I.e. the first synthesis step has to be performed by humans or is based on pre-defined solution patterns, only then can the software start with an analysis phase. Optimisation methods/tools can currently only handle a very limited number of properties (e.g. mechanical

stress and weight in structural optimisation). The challenge is to develop practicable multi-criteria optimisation methods that can cope with real life applications.

Today, CAD and, increasingly, PDM systems are regarded as core tools of the product development/design process. However, they only represent characteristics: The parts' structure, geometric and material data, and dependencies between characteristics in the case of parametric systems. If they are not enhanced by "digital solution patterns/elements", like features, templates, etc., they cannot contribute anything to determining properties (analysis) or deriving characteristics from required properties (synthesis). Their importance comes from the fact that the parts' structure, geometry, and material data are necessary inputs to determine practically all relevant properties – with the analysis itself performed by other tools. The challenge is that different analyses (in different phases of the process, addressing different properties) require different sub-sets of the characteristics stored in CAD and/or PDM. In conclusion, the role of CAD and PDM systems is in "service" rather than "core", with the requirements coming from the "real" analysis systems.

Documenting Development/Design Results

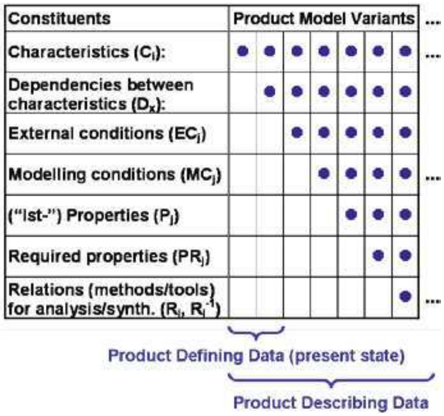
The key issues connected with documenting the results of product development/design processes are clarification of the possible constituents of product models, and defining which ones are needed. These issues cannot be discussed in depth here, but a few ideas can be outlined.

Using the CPM/PDD approach (Section 8.3, in particular figure 8.6), potential constituents of product models are:

- characteristics of products ($\mathbf{C}_i$)
- dependencies between characteristics ($\mathbf{D}_x$)
- external conditions ($\mathbf{EC}_j$)
- modelling conditions ($\mathbf{MC}_j$)
- properties of products, further split into as-is ($\mathbf{P}_j$) and required properties ($\mathbf{PR}_j$)
- relations linking characteristics and properties ($\mathbf{R}_j$, $\mathbf{R}_j^{-1}$), i.e. the methods and tools used.

Different combinations of these produce different product model concepts (figure 8.7), which should be studied for their advantages and shortcomings.

What exists today is almost exclusively characteristics ($\mathbf{C}_i$), stored in CAD and PDM systems: Parts' structures, geometric and material data, as well as geometric and spatial dependencies in parametric systems (i.e. a sub-set of $\mathbf{D}_x$).



Constituents	Product Model Variants							...
Characteristics (C_i):	●	●	●	●	●	●	●	...
Dependencies between characteristics (D_x):		●	●	●	●	●	●	
External conditions (EC_j)			●	●	●	●	●	
Modelling conditions (MC_j)				●	●	●	●	...
("Ist-") Properties (P_j)					●	●	●	
Required properties (PR_j)						●	●	
Relations (methods/tools) for analysis/synth. (R_i, R_i^{-1})							●	...

Product Defining Data (present state)

Product Describing Data

Fig. 8.7 Potential constituents of product models and selected combinations

If more than the ultimate outcome of the product development/design process represented in product models is desired, operational representations of product properties are urgently required (both as-is, $\mathbf{P}_j$, and required properties, $\mathbf{PR}_j$). "Operational" means that storing files that contain statements about properties (as in current PDM systems) and text-processing requirements lists (as in current Requirement Management Systems, RMS) is not sufficient. Instead, meanings and values of properties must be captured. Otherwise it will never be possible to capture and trace the individual steps (cycles) of the development/design process and the reasoning behind them (the design intent) because it is all controlled ("driven") by the properties.

Moreover, during the development/ design process, properties and characteristics of a product go through several states (modified and expanded from cycle to cycle). Therefore, concepts for dynamic product models/modelling are needed.

Defining and implementing adequate product models is the biggest challenge on the journey to enhanced computer-support of product development/design processes. At the same time, this task really needs knowledge and experience from Design Theory and Methodology.

Controlling the Development/Design Process

In the CPM/PDD approach, the product development/design process is controlled ("driven") by the properties: by determining the current set of as-is properties ($\mathbf{P}_j$) by analysis, evaluating them against the required properties ($\mathbf{PR}_j$), then drawing conclusions for subsequent synthesis steps (figure 8.5).

Therefore, all issues discussed in the two sub-sections (on analysis and synthesis tools and more comprehensive product models) are prerequisites for extensive computer support of product development/design processes as a whole. However, computer-based methods/tools are required that can support overall evaluation of the current solution-state within the process and conclusions drawn about the next synthesis step(s). Both issues require some basic research first; for the latter it may not even be clear whether computer support is feasible (and, if so, to what extent).

So far, all aspects considered concentrated on the product development/design process itself. However, in academia as well as in practice, the focus is widened to follow the product along its entire life, including all phases after product planning and development/design. The most prominent concept for this is PLM (Product Life-Cycle Management). Therefore, some additional conclusions on PLM, derived from the CPM/PDD approach, will be shown.

Figure 8.8 (which is based on the product development/design process scheme in figure 8.5) displays the basic concept of following the product along the life-phases after development/design being facilitated by taking the product's actual behaviour in later phases into account. This can be represented by "as-experienced" or "life-cycle" properties ($\mathbf{PL_j}$). This enables:

- Life-cycle monitoring: Comparing as-experienced properties ($\mathbf{PL_j}$) with as-determined properties ($\mathbf{P_j}$). If major deviations are found, then something is wrong either in the use of the product or in the development/design process (e.g. inadequate analysis methods). The latter must lead to an urgent improved deployment of methods/tools, thus improving future processes.
- Systematic requirements development: Comparing life-cycle properties ($\mathbf{PL_j}$) with required properties ($\mathbf{PR_j}$). This can improve the starting point (and probably the end or outcome) of the development/design process for the next product or product generation.

Properties have to be represented and compared to realise the new functions – a key issue, as discussed previously.

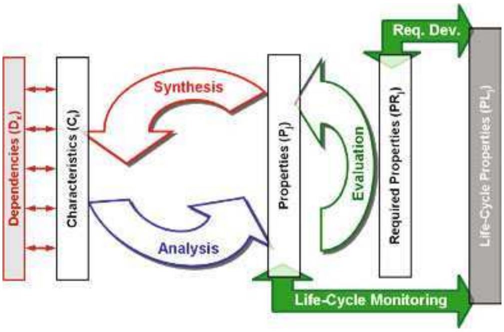


Fig. 8.8 Extending the focus to "as-experienced properties" (life-cycle properties, $\mathbf{PL_j}$) as a base for PLM (Product Life-Cycle Management)

8.5 Conclusions

Based on a conference paper of Weber and Birkhofer (Weber and Birkhofer 2007), this chapter investigated the contributions of Design Theory and Methodology (DTM) to the progression, systematisation and application of computer methods/tools for product development/design. The results and proposals do not present final solutions, especially as the general approach shown here may be regarded as quite particular.

However, this chapter is an attempt to get DTM more involved again in the progression, systematisation and application of computer methods/tools for product development/design. In an optimal situation, this chapter will spark off broader discussion about the topic, with DTM ultimately determining the development of CAx, not vice versa.

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Chapter 9
Summary - Specific Approaches to Further Develop Design Methodology

H. Birkhofer

A large group of authors have formulated precise proposals for further developing Design Methodology concerning individual topics or better links between subject areas. The chapters in this category relate to individual development phases or cross multiple phases. The basic structure of Design Methodology, with its phases arrangement, sequential course of action with iterations, allocation of methods and specification of phase-related results, is widely used and accordingly not questioned.

9.1 Intensification and expansion of existing research focuses

The first subgroup makes concrete proposals of how existing research focuses can be deepened or extended appropriately to deal with deficits and changed requirements.

Andreasen and *Howard* shed light on research in Embodiment Design with the question "Is Engineering Design disappearing from design research?". In contrast to several works from the 1950s and 60s, the subject of Embodiment Design only plays a minor role in today's design research, although its relevance to industry is still current. An initial conclusion is the separation of Embodiment Design into its preceding and successive phases. In design practice, this separation can be less rigid as the procedures in classic Design Methodology imply. The borders to conceptual design and to detailed design are blurred. To fulfil life cycle requirements, summarising Engineering Design and Embodiment Design seem necessary. Especially for complex requirements (e.g. safety or reliability), appropriate decisions can only be made if specific scenarios within the life cycle are comprehensively thought out and solutions in the Embodiment and Detail Design phase are developed with the help of Engineering Design. Structuring of the product in modular structures (platform design, multi product development) is essential to Embodiment Design. Further challenges include increasing the effectiveness of Embodiment Design work to radically reduce the number of design changes, design iterations and product recalls. The question remains of whether people really think in the models derived from analytical consideration and in the categories of Embodiment Design and Detail Design. How do designers interact with the immense

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number of changes in a product's life? What do their mental models of objects and properties look like? Which thought patterns are used to fulfil requirements within the life cycle? These questions and others require a "new" orientation of research in Engineering Design. To date, this area has barely a theory, barely a language; Embodiment Design is not yet understood.

In "Methodical support for the development of modular product families", *Krause* and *Eilmus* focus on the problem of variants in modularized products and suggest a new and more efficient kind of variant management. It relies on holistic examination of the properties of modularized products, its structures and its processes throughout its life cycle. To reduce internal variety without influencing the desired external variety, the authors propose product and process related strategies. With product-related strategies, the modules and the platforms of its functionality can be determined. Process-related strategies target multiple usage of the same process for different products and shifting variant-dependent processes towards the end of the process chain. The application of these theories is supported by visualising systems. These systems present the whole range of properties, functions, active principles and components in their relationships, far exceeding the classic illustration of variants that only consist of parts and assemblies. Individual modules in every life-phase are determined and their allocation is visualised over their life cycle. With this, the module-drivers can be identified in a clear and comprehensible way. Specific modules can be evaluated for their process-related effort.

In their contribution "Risk-driven design processes: Balancing efficiency with resilience in product design", *Seering* and *Oehmen* examine a cross-sectional task within the development process. They highlight the relevance of extensive risk examination, especially in complex development tasks. This risk examination extends the mainly efficiency-targeting, conventional Design Methodology with an intentional consideration of uncertainties in all development phases. The methodology of this risk assessment structures the sources of uncertainty, such as processes and methods, labour and skills, financial resources, customer requirements, cultural norms and technology. The method of risk-driven design, with its principles, is based on this. First, the greatest possible transparency in nature and appearance of risks has to be achieved. These risks then have to be accounted for in all decisions within the development process to minimize the identified uncertainties. Finally, resilience has to be implemented into the developed system to mitigate unforeseeable uncertainties. This procedure augments the known risk evaluation with a holistic approach that integrates known risk-management methods.

9.2 Improvement of the revision of work in human-computer relations and the integration of computer usage into Design Methodology

Three contributions address the problem of insufficient integration of computer usage into methodical design.

In his contribution “Methodology and computer aided tools – a powerful interaction in product development”, *Meerkamm* focuses on developments in Design Methodology and computer usage in general. While Design Methodology is growing only marginally, computer usage is highly dynamic. To fulfil future requirements to products in a global economic system, close interaction of methodology and computer usage is indispensable. The contribution starts with an overview of both topics. Then, using several examples from DFX, calculation and simulation, tolerance analysis and process modeling, the successful combining of Design Methodology and computer supported tools is proven. In the future, it will be necessary to further this integration into all areas of product development. A huge benefit can be expected if computer integration is successful, especially in the development of customised design methods for specific applications.

In *Feldhusen*, *Nagarajah*, *Schubert* and *Brezing’s* contribution, “A reuse design decision support system based on self-organising maps”, a way to access previous results specifically with computer aid to make further development more efficient is presented. This approach is called “Reuse Design”. Using product data and experiences from earlier products as a starting point for further development is a promising option. Therefore, earlier developed products are sought whose requirements match those of the current development project. With this approach, an adaption or variant design can be used, instead of a time-consuming new development. To generate the necessary comprehensive comparison of requirements, a variety of requirements have to be registered, normalised and compared to further derive an appropriate decision over the keeping or changing of parts and components. At this point, the contribution proposes to transfer the search and standardisation of requirements to a computer that also visualises the search results in a quickly ascertainable graphical form. The task of the designer in this reuse-process is to control single intermediary results, draw accurate conclusions from the results and determine the most applicable product for reuse. Human and computer are included in this complex planning process according to their specific abilities, so that the methodological approach is systematically extended with the use of experience and data from preceding products.

In their contribution “Increasing effectiveness and efficiency of product development – a challenge for design methodologies and knowledge management”, *Binz, Keller, Kratzer, Messerle* and *Roth* use powerful IT techniques to generate specific knowledge during the development process. Their approach is based on the need for individualised, customer-specific products increasing in a globalised world. The generation of successful product ideas is becoming a key factor in companies. To evaluate ideas for their chance of success and to divide the variety of ideas in a purposeful way, methods can be used to provide the “proper” knowledge at the “right time”. With a coherent set of requirements for such methods, deficits in the current method-based support for knowledge allocation and initial solutions are presented with the help of four case studies (e.g. the development of Hybrid Intelligent Design Elements (HIKE)). A first, directly applicable solution approach is the extension of a Wiki. Multi agent systems are distinctly more powerful techniques since they act semi-autonomously. As CAD agents, they provide information on parts and connections. As management agents, they control the consistency of CAD models. Further work applies to the evaluation of development-relevant knowledge in the specific case of application. Therefore, a catalogue of criteria has been developed.

9.3 Fortification of the scientific foundation

To create a comprehensive Design Methodology, findings and recognitions should be generalized on a strong scientific fundament.

In comparison with the above contributions, Weber follows a different approach based on scientific consideration in his contribution “Design theory and methodology – contributions to the computer support of product development/design processes”. He promotes the benefit of the Characteristic-Property Models as a scientifically profound base for the development of a new concept for comprehensive use of powerful computers. In this model, the characteristics represent the product properties that can be influenced directly during the design process. From these characteristics, the properties result as perceptible, often measurable properties in the entire life cycle. The relations between both model elements are frequently used within the conventional development process to analyse existing product models and compose new models. The author transfers the fundamental relations derived from property theory to computer usage. A thorough compilation of a list of requirements based on systematic analysis of the product life cycle can be transformed incrementally into optimal product documentation by using computer-aided analysis and synthesis tools. With each work step, the requirements and properties are comprehensively described and consequently compared to minimize divergence between the two. The approach requires powerful analysis, only partially developed, and synthesis tools that far exceed current CAX capabilities.

9.4 Results and recognitions

Most of the authors justify the call for further research with the requirements of future products and services within the life cycle and from demands for a more powerful development practice (Figure 9.1).

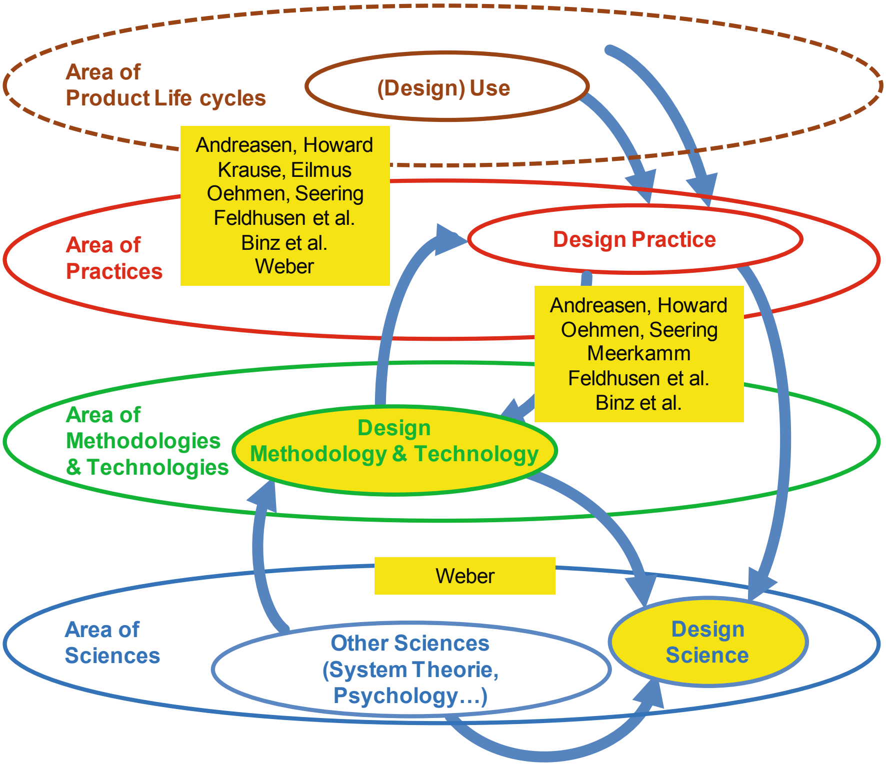

Fig. 9.1 Classification of the contributions in the section "Specific Approaches to further develop Design Methodology" with regard to their research approach

All authors describe specific research work to further develop design methodological procedures mostly with a strong emphasis on the integration of computer usage into Design Methodology. With the exception of Weber the contributions are pragmatic approaches to identify concrete needs for action in development practice and to propose similarly concrete solutions to fulfil these needs. In contrast, Weber suggests reconsidering the use of analysis and synthesis tools from a design science consideration of product properties, to determine their design mainly from a comparison of requirements and properties of product models. In the sense of a consolidation of Design Methodology, this long-term approach has particular relevance since it shows a possible way of accounting for the growing requirements of design practice.

Part II
Holistic Ways to Supply, Extend or Replace Design Methodology

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Summary - Holistic Ways to Supply, Extend or Replace Design Methodology

Chapter 10
Boundary Conditions for a New Type of Design Task: Understanding Product/Service-Systems

T. C. McAloone[1]

Abstract: Manufacturing companies have traditionally focused their efforts on developing and producing physical products for the market. Currently, however, many companies are rethinking their business strategies, from selling products to providing services. In place of the product alone, the activity and knowledge associated with the use of the product is increasingly perceived to be the new design object. But how to organise the design of combined products and services, over expanded time domains and new stakeholder boundaries? The design research community is paying increasing attention to this new design object and research paradigm, studying service-oriented approaches to product development and seeking to understand how to spell the systematic development of these so-called Product/Service-Systems (PSS).

When considering the shift towards PSS in the domain of engineering, it is interesting to understand the shifting focus and identification of *boundary conditions* that manufacturing organisations must undergo, in order to develop just as systematic an approach to the service-related aspects of their business development, as they have in place for their product development.

This chapter will attempt to map out some of the boundary conditions for PSS design research, in order to ensure that the phenomenon is successfully transformed into a well balanced design research field, including the necessary domains of expertise and research content to fully understand, develop and also communicate the field to industrial manufacturing companies.

10.1 Introduction

In the current transition in the business mode of manufacturing enterprises, an enriched focus is being placed on the value enhancements of products and services (Tan 2010). In this situation, new relationships, responsibilities, objects of development and transactional issues are beginning to arise. Traditional organisational and temporal boundaries that have characterised manufacturing and service-based organisations, respectively, are no longer so clearly defined. Car and aircraft

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manufacturers are, for example, experiencing increasing revenues from before- and after-sales service, and banks, on the other hand, now place physical boxes with barcodes on the shelves of local branches, in an attempt to make tangible their own developed products; for example, a loan (Morelli and Nielsen 2007).

In the domain of engineering it is important to trace and attempt to foresee the adjustments that organisations must undergo, in order to remain competitive in the business creation process, when the boundary conditions for business creation are constantly changing, in relation to a traditional production-sales situation. No longer is it sufficient to have a systematic approach to product development and production alone, when increasing proportions of revenue are coming from before- and after-sales service (Tan 2010). For many organisations, it is a culture shock to imagine the transformation of a cost-centre (as many after-sales activities traditionally have been viewed by many companies) over to a profit centre, where an adjustment of the relationship to the customer is necessary (Wise and Baumgartner 1999). But as the business foundation for more and more companies is increasingly based on service revenues than on those gained by selling the physical artefact itself, there is a large desire to understand and control the processes that surround this augmented business model.

The design research community is currently responding to this phenomenon by creating and running research projects, groups and alliances, with the aim of understanding and developing approaches to product/service-systems (PSS). So far the *PSS design research community* is emerging largely from the manufacturing and engineering design domains of academia (where PSS had its infancy in the field of ecodesign). As with all new phenomena, the initial strategy adopted to map and understand the field is largely based on own reference models, language and theories. However, as the field of PSS extends far beyond the design or manufacturing processes, into the extended lifecycle of a product and activity cycle of the user, a purely engineering focus must be rendered as insufficient (Matzen 2009).

This chapter presents an attempt to map out some of the boundary conditions for PSS design research. Boundary conditions are described here as a series of tensions, which define the solution space within which the PSS design research field resides. The tensions described are: from engineering to innovation; from product to service; from design to doing; from regulation to choice; from user activity to provider offering; and from quality to value.

10.2 Broadening Horizons through Boundary Conditions

The motivation for taking this excursion into the boundary conditions for PSS is based upon a desire to understand the nature, contents, roles and relationships existent, in a PSS design and delivery situation. The literature in the field of PSS has, until now, been focused largely on the actual transition from product to product/service-system, and has therefore typically resided in the fields of engineering design and product development, both of which have a firm basis in the understanding of systematic approaches to the realisation of physical products. Symptomatic of the current literature is the concept of service as the adding-on of non-physical activities and relationships between supplier and customer.

Jørgensen & Sørensen's (Jørgensen and Sørensen 2002) conceptual framework of development arenas has been adopted for this exercise, in order to help to describe the PSS arena that emerges within the boundary conditions identified. According to Jørgensen & Sørensen (2002) a development arena consists of:

- actors (i.e. people and organisations), objects and standards;
- logical and physical locations where changes occur; and
- translations that stabilise and destabilise relationships.

The boundary conditions described in the following were identified through a series of theoretical and empirical studies, where the aim was to understand characteristics and strategies for the design and development of PSS (McAloone and Andreasen 2002, Matzen 2009, Tan 2010). They were observed to be particularly characteristic to the design of a PSS offering, compared with integrated product development as the baseline for "traditional" product development activity. The six identified boundary conditions for a PSS development arena, are illustrated in figure 10.1.

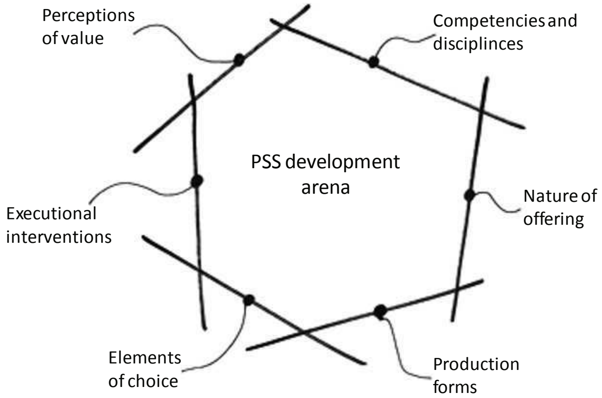

Fig. 10.1 PSS development arena and its boundary conditions

The PSS development arena should not be seen as an alternative or a competing paradigm to a product development arena or methodology, but as a supplement, with respect to the augmented design object that is necessary to understand, when conceptualising a product/service-system. The proceeding section will work clockwise around figure 10.1, describing and discussing each element in turn, and pointing to characteristic PSS elements in each case.

10.3 Six Composite Views of PSS

As a design research field PSS, is a new and emerging area, where the definition and study of ‘functional sales’ (Stahel 1997), ‘functional (total care) products’ (Alonso-Rasgado et al. 2004), ‘servicizing’ (White et al 1999) and ‘service engineering’ (Tomiyama 2001) all have contributed to the foundation and our current understanding of PSS as a phenomenon.

In the meantime, the latter half of the 2000’s has seen a particularly increasing interest in PSS design methodology, from a broader and more multi-disciplinary group of researchers, representing engineering, technology management and economical disciplines (e.g. Baines et al 2007). Thus the PSS arena described here is still in its formative stages, where definitions, understandings and approaches to the field are still fluid. Nevertheless, the following gives six views on PSS design.

10.3.1 Competencies and Disciplines (from Engineering to Innovation)

The first identified boundary condition for the PSS development arena discusses competencies and disciplines necessary for PSS design and operation. According to Tan et al (Tan et al. 2006) the underlying strategic principle of PSS is to shift from business based on the value of exchange of product ownership and responsibility, to business based on the value of utility of the product and services. This implies a fundamental reassessment of core business, ownership, transactions, development and delivery of the ‘offering’ (this term is chosen so as to avoid confusion about the nature of a product or service), and client-customer relationships.

Thus the object of value for the providing company transforms from merely the physical artefact, to any chosen and targeted transaction between the customer and the providing company. Compared to traditional product development, a new set of competencies must be present in the PSS design activity, to enable the design, development and maintenance of a satisfactory relationship with the customer, who is in a closer (and often contractual) relationship with the providing company.

It is our belief that there are a certain amount of generic types of PSS that can be typified and thus supported by methodology (Tan and McAloone 2006), but this hypothesis is not yet explored to full conclusion. We can already observe, however, that compared to a traditional product development activity, a PSS project is dependent on a much broader set of competencies in the design activity (logistics, economics, IT, law and marketing, etc.). This may not seem surprising, as a PSS is, by nature, much more than the engineered artefact itself. The interesting factor here is, that when designing and developing a PSS, the producing company needs to regard both product, product life cycle and the user’s so-called activity cycle as the development object – thus the need for a broader representation in the development arena.

Furthermore a PSS requires an orchestration of a complex network of stakeholders, both in- and outside of the company, in order to deliver an augmented product to the customer in a satisfactory manner – and thereafter to sustain this satisfaction throughout the whole provider-user relationship.

10.3.2 The Nature of the Offering (from Product to Service)

PSS has until now been regarded as the joint development of product and service, plus the providing company's subsequent delivery of services to the customer – when bundled together, dubbed "a system" (Tukker and Tischner 2004). Our own research in the field of PSS has so far convinced us that the behaviour of services and products in the use phases of the product's life are identical (McAloone and Andreasen 2002). We therefore see the need to arrive at more usable descriptions and definitions of product, service and PSS, linking to an integrated understanding of customer-oriented value and utility, thus freeing ourselves of the artificial distinction of [PSS = product + service].

McAloone and Andreasen (McAloone and Andreasen 2002) take a domain-oriented view of PSS, where a PSS offering is described in terms of an artefact domain; a time domain; and a value domain. This view is closely inspired by Ropohl's (Ropohl 1975) system technical theory. In each domain it is possible to describe the key distinctions and innovative developments that a company must undergo in order to create sustained value, customer lock-on and flexible solution-oriented business offerings to the customer. These domains help to formulate a system of characteristics – or ontology – of the product/service-system, as follows:

- In the time domain a PSS is a sequence of multiple, interrelated life phases and activities throughout the product's service time, i.e. the period where it is utilised in accordance with its planned purpose (the product seen as *Sachsystem* – (Ropohl 1975)).
- In the artefact system domain (*Handlungssystem* – (Ropohl 1975)), it is a set of multiple, interrelated systems, between which the product life phase system of use is the pre-dominant, but where other systems (the producer's maintenance system, the overall system related to the product, the supply of input to the product, etc.) can also be of importance.
- In the value domain (*Wertsystem* – (Ropohl 1975)) it is a set of multiple stakeholders' values, determining the utilisation and reactions to the artefact systems and activity systems effects and determining how seriously the side-effects are regarded (according to Eekels (Eekels 1994)).

It is important to observe that the traditional pattern of a manufacturing company's share of the product life cycle, followed by the owner's share of the product life, and finally the undefined ownership period, followed by disposal, shall now be viewed in a new way. The company's business intent, the user's intent in the product's materialisation and their joint interest together with the artefact throughout the entire life cycle, ought to give new opportunities for innovative thinking and co-development.

In an attempt to create a new lens for design, which does not muddle the definitions of product and service, figure 10.2 presents a palette of "offerings", which vary in nature and content; most of which can be engineered, and all of which can contain both products and services.

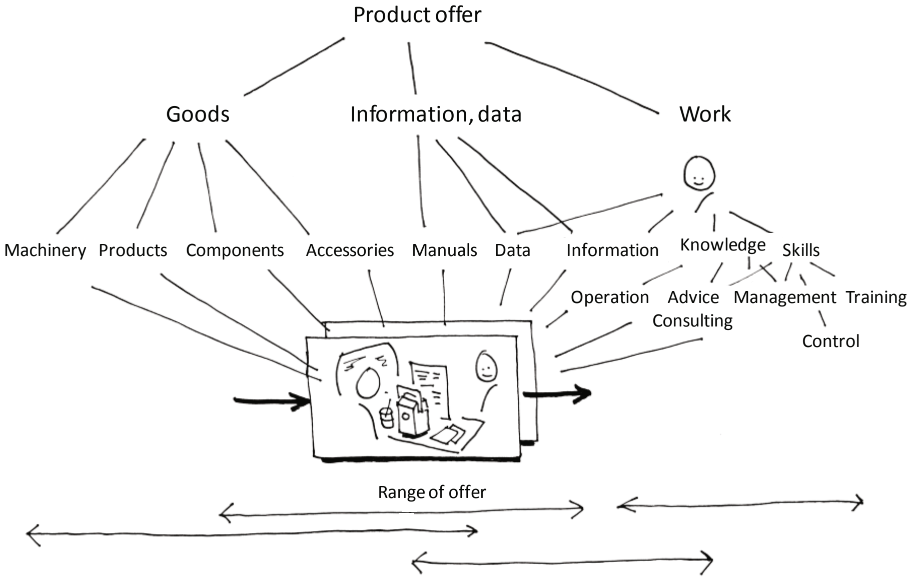

Fig. 10.2 The varying nature and content of offerings.

10.3.3 New Production Forms (from Design to Doing)

The shift towards PSS for industrial companies can be described from many viewpoints, ranging from the desire to support a post-industrial society, the increased competition (and opportunity) to support an increasingly dematerialised world, to a necessary decoupling of competitive edge from cost, quality, time, and so forth. The current discussion of these reasons and observations of the augmentation of organisations' interests in usability, use and service is pointing towards the definition of new production forms (Andersen et al 2007). The Nordic countries are, for example, currently investing large resources in the research field of new production forms (DASTI 2006).

The company that experiences a declining income from goods-related offerings (towards the left-hand side of figure 10.2) as opposed to an increased activity – and in some lucky cases, income – from work-related offerings (over to the right-hand side of figure 10.2), should begin to define and develop new production forms, that combine a systematic development of all relevant types of offering depicted in figure 10.2, not merely goods-related.

There are a number of approaches towards implementing and integrating new production forms into the organisation, that are highly relevant to successful PSS design. By broadening the perspective from product life cycle to customer activity cycle (Vandermerwe 2000), we expand the design object for PSS. And by placing the customer in focus and understanding their needs for functional, efficiency-based and/or social fulfilment (this weighting differs, dependent on B2C or B2B), it is possible to develop a competence- and network-based approach to supporting the customer's whole activity – and not merely providing a physical good.

We can therefore describe the definition of new production forms as a shift in focus from 'design' to 'doing'. User-driven innovation is currently seeing a renaissance as a research field (Kristensson et al 2004, Chesbrough 2006), where an earlier and more limited focus on voice-of-the-customer has developed into a range of user-oriented innovation activities.

One such user-oriented innovation activity is *open innovation* (Lindegaard 2010), where the philosophy of externalising some of the company secrets of the previous goods-dominated paradigm leads to the co-development of user-oriented solutions.

10.3.4 Elements of Choice (from Regulation to Choice)

As previously implied, PSS design should be based upon new degrees of freedom in the design process, due to a more broadly defined design object, closer contact with the end-user and an extended service period, compared with traditional business. But what should a PSS give the user, seen from their perspective?

From empirical observations (McAloone and Andreasen 2002, Matzen 2009, Tan 2010) we can state that from the user's viewpoint, a PSS will only be attractive if it (i) adds more value than normal product ownership (measured by level of prestige, ease of ownership, price, total cost of ownership, etc.); (ii) gives greater degrees of freedom than a traditional product (ease of upgrading, guaranteed take-back of goods, possibility to focus on core business, etc.); and/or (iii) includes greater elements of choice to the user.

Traditional mass-produced products (anything from software to vacuum cleaners) come with in-built and implicitly regulated properties, that the user must reconcile him/herself with, or find out how to work around, if the properties limit the intended use. A large opportunity of PSS, on the other hand, is that the user is present in the specification of use and usability, leading to the creation of choice, as opposed to living with in-built regulation.

10.3.5 Executional interventions (from User Activity to Provider Offering)

As PSS is a broadly used term, covering many types of industry, sectors, organisational traditions and customer relations, it is safe to state that there can be many classifications of PSS. Tucker and Tischner (Tischner 2004) offer a tripartite definition of PSS, ranging from product-oriented, through use-oriented, to result-oriented. Tan and McAloone (McAloone 2006), on the other hand, take a morphological approach to understanding PSS types and characteristics, based upon observations of a series of cases. In this morphological approach it is interesting to observe the varying types of *executional interventions* (exchanges between provider and user, product and user, product and provider, etc.), describing which party is active or responsible for certain key activities and elements of the PSS.

The conceptual development of a PSS should include the consideration of which executional interventions to build into the final solution, and what nature they should have. Examples of high-level executional interventions include: responsibility during use; management of life-cycle activities; and type of availability of the offering. These high-level interventions can be further broken down into sub-classifications of interventions, throughout the scope of the PSS.

We feel it important to think in terms of executional interventions, as this gives useful insight into the key activity dimensions of a PSS; areas which normally are *not* up for discussion when designing a traditional artefact. This viewpoint ought to give the PSS designer the insight into how active or passive the user is in each element of the PSS concept and in which situations to choose whether to delegate or to keep responsibility for the good, the information, the service, and so on.

10.3.6 Perceptions of Value (from Quality to Value)

The engineering community has focused for many years on effective approaches for ensuring high value products and systems. The challenge here has been in matching the customer's judgement of value (subjective evaluation of goodness vs. investment incurred) with the company's own ability to provide products of high quality. In an attempt to bring Design for Quality as close as possible to an understanding of users' requirements, Mørup (Mørup 1993) created two classifications of quality: Q-quality ("big Q"), which refers to the customer's qualitative perception of the product's goodness; and q-quality ("little q"), which represents the internal manufacturer's perception (and measurement) of the product's goodness.

This approach has recognition in certain academic circles, and has furthermore been implemented as a concept in a number of industrial companies. It stands in stark contrast to the quality-control oriented designing-out of 'bad qualities' and is more proactive in its designing-in of 'good qualities'. However, Mørup's approach is still based on a somewhat distanced relationship between manufacturer and user/customer, where the product developer first envisages and later prays for the correct user reaction to designed-in qualities, without necessarily asking the user first.

The very nature of PSS design – where the relationship with the customer is designed to be longer and more intense; where focus is given to functional provision and not merely sales of artefacts; and where the product life view is matched with a customer activity view – gives many opportunities for the development task to come much closer to an understanding of value perception than in a traditional product development situation.

10.4 Case: PSS in the Maritime Industry

To synthesise these thoughts about a PSS development arena and describe the boundary conditions for PSS in one common example, the following case describes a PSS activity in the Danish maritime branch.

In the shipbuilding industry the continuing market globalisation, as in many other sectors, both opens opportunities in terms of a rising number of potential customers and represents threats, due to the growing number of competitors worldwide. The Danish shipbuilding industry has traditionally relied on the longevity and high technical and functional qualities of their physical products to create competitive advantage. However, these quality parameters are increasingly under pressure in current global markets, where many competitors offer functionally comparable components at substantially lower prices, and where quality differences are not readily visible to customers. Furthermore, the maritime component supplier companies' position as sub-suppliers in the supply chain to contracting shipyards traditionally leads to compromises, as the shipyard often makes decisions based upon low first purchase cost, in order to keep their own sourcing expenses (and therefore the initial cost of the resulting ship) as low as possible.

Some suppliers now see the potential of providing support services for their equipment and related installations, especially in cases where ship owners are moving over to a *total cost of ownership* mindset, in contrast to shipyards' *first purchase cost* mindset, which has significantly lower PSS development potential. The challenges connected with shifting business perspective from product manufacturing to service delivery are manifold, and the following list represents only some of the important aspects that should be understood and considered:

1. understanding of products' life phases and activities
2. identification of valuable service offers
3. development of delivery networks
4. development of internal delivery systems
5. marketing of service offers to (new) customers
6. altering the practices of users and customers
7. dynamically adapting and improving service offers (Matzen and McAloone 2008).

In recognition of this need, a Danish research consortium comprising 12 companies from the maritime branch is currently focusing on the definition of systematic approaches to PSS. Understanding the need to define new production forms (based on a range of goods, information and work) and PSS opportunities that are less dependent on straight component manufacture is key to the project, as all of the companies can see a shift in the relationship between product vs. service, with respect to income sources and competitive edge. The opportunities for using open innovation as ways in which to collaborate across numerous companies in the consortium are enabling new PSS concepts and innovative ways of providing service to the customer (the ship owner) in their activity cycle. Through a systematic charting of each of the 12 companies' exectuional interventions through chosen PSS and after-sales examples, a morphology of PSS types is being compiled, in order to investigate the amount of generic PSS types that can be identified and thus developed.

Going one level deeper into this consortium one can observe one of the twelve companies, which has already recognised the need to-, and the opportunities that can arise from developing new production forms. MAN Diesel, the leading manufacturer of large bore two-stroke diesel engines for marine applications effectively suspended in-house manufacture of these engines in the 1980'ies and has since focused on technology development, design and maintenance services, while virtually all physical manufacturing of large two-stroke engines is outsourced to licensees on a global scale (Matzen 2009). The company refocused their activities completely from manufacturing to engineering and life cycle support, which is offered by the company's PrimeServ division. Needless to say, an operation like this requires full control over activities, artefacts and service infrastructure, in order to provide value-added service to the customers and a substantial refocusing has been carried out, regarding the organisation's competency profile.

10.5 Discussion and Conclusion

This chapter aimed to map out some of the boundary conditions for PSS design research, in order to present a PSS development arena and begin a discussion of the key differences and characteristics of PSS design. Six composite views were presented and discussed, in terms of each their particular characteristics. The views were gained from empirical work, but in their current form presented in a relatively kaleidoscopic fashion. This suggests that there is, as yet, little structure to follow when describing and discussing PSS.

The complexity of DFX as an application area, and therefore as a research field, is worth noting. As integrated product development was to engineering design, so it seems that PSS is to integrated product development, raising complex questions about competencies, time, value, collaboration, market understanding, and so forth. Nevertheless it seems that creating a methodical way of understanding PSS types, collaboration models and customer activities gives rise to promising insights and a potential foundation for new ways of defining the designer's role in product development.

Our continuing research work in this field endeavours to further structure and describe the PSS activity as a design task, even though we are fully aware that the very notion of design is also set in a new light, in the context of PSS.

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Chapter 11
Product/Service System Design and Beyond

T. Sakao[1]

11.1 Introduction

Manufacturers in developed countries today face severe competition from hardware manufacturers in low-wage countries. This competition is expected to become tougher as the quality of products from manufacturers in developing countries improves. Firms in developed countries need to find ways to distinguish themselves in terms of value for customers. Product quality is part of this value. Service is also an important element that creates value for customers. Manufacturers in developed countries regard service as increasingly important. Some manufacturing firms are strategically shifting from the role of "product seller" towards "service provider" (Oliva and Kallenberg 2003). Importantly, service activity is increasingly being incorporated into the design space, an area traditionally dominated by physical products in manufacturing industries. Companies expand the aim of engineering design from a physical product to include products and services, so that the whole design is effective and efficient. Such an offering is often called Product/Service Systems (PSS) (Mont 2002; Tukker and Tischner 2006).

The importance of this expansion has been recognised by the design community in the last decade (Brännström et al. 2001; Tomiyama 2001; McAloone and Andreason 2004; Sakao and Shimomura 2004; Roy and Baxter 2009; Sakao and Lindahl 2009). Various groups have presented concepts and methods to support the expansion, such as Functional Product Development (Brännström et al. 2001), Functional Sales (Lindahl and Ölundh 2001), Integrated Product Service Engineering (IPSE) (Lindahl et al. 2006), and Service Engineering (Sakao and Shimomura 2007). These concepts share a commonality of design aim that comprises combinations of hardware and support services. The large amount of research in this area in the last decade means that questions can be raised. Have researchers been doing the right things? Where should research be heading?

Having these questions in mind, the aim is to review PSS design research as well as future research issues. A new concept that goes beyond PSS design is then presented: integrated development of technology and the business model.

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Section 11.2 explains how PSS design is an expansion of engineering design of a product, and reviews PSS research. Section 11.3 introduces the idea of integrated development of technology and the business model, while Section 11.4 concludes the chapter.

11.2 Nature of PSS Design: Differences from Traditional Engineering Design

11.2.1 Three Dimensions to be Considered

PSS (Product/Service System) consists of "tangible products and services designed and combined to jointly fulfil specific customer needs" and is also a value proposition, which includes the network and infrastructure (Tukker and Tischner 2006). PSS design addresses the customers, while the functions of physical products and provider's activities are measures that create effects. The provider's activities, such as maintenance services, are included in the usage process, and customer evaluation is paramount.

Approaches to PSS design involve changes in the traditional design procedures, delivering processes, and engineer mindsets. Therefore, it has a lot of influence on a provider. (Sakao et al. 2009b) argued that three dimensions are necessary to form the space used to map the elements for PSS design and other connected research: the offer, the provider, and the customer/user. The first dimension refers to both "product" and "service" elements of PSS. The other two dimensions, i.e. the provider and the receiver, are indispensable in addressing PSS.

The offering dimension addresses the elements and activities in the lifecycle. It includes the lives of physical products that are part of the PSS, as well as service activities. Successful design of PSS depends on a thorough understanding of the solution lifecycle and active design of beneficial linkages with the heterogeneous systems involved.

The provider dimension addresses the evolution of product/service providers' organisations and operations. This covers such issues as the setup of development projects, organisational streamlining of the company for service delivery and the identification of partnerships needed for successful operation of services.

The customer/user dimension addresses the evolving needs of service receivers. It is crucial for the provider of services and products to anticipate receivers' reaction to new offerings.

In principle, any PSS design is supposed to address at least part of all three dimensions, since service includes the activities of customers and providers, and because products are included. This characteristic of service is represented by the term "co- creation" (Spohrer and Maglio 2008). As such, the three dimensions are fundamental to PSS design. In addition, anticipating and utilizing the dynamics along each dimension is crucial. This implies that the essence of PSS design, especially when compared to traditional engineering design, lies in the utilization of the dynamics of and between offer, provider, and customer. Figure 11.1 illustrates the links of some of the research topics to the three dimensions.

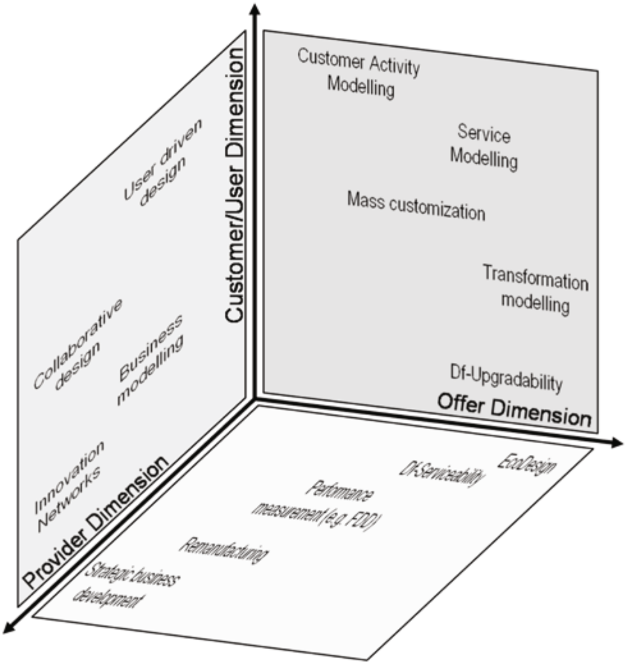

Fig. 11.1 The three dimensions of PSS design (Sakao et al. 2009b)

11.2.2 Reviewing Design Research on PSS

Researchers in the EU-funded Suspronet project (Tukker and Tischner 2006) have contributed extensively to PSS research. They mainly take an analytical view of engineering design, not a synthetic one. The product-service continuum (from product-oriented, use-oriented, to result-oriented service) is useful for *classification* as a part of the analytical phase of design (Table 11.1). In addition, the research reported in (Tukker 2004) is the result of *analysis*. Other literature, such as (Mont et al. 2006), is also analytical. This means that findings from this group of PSS researchers are limited to designing offerings.

A group of PSS researchers focusing on design has emerged relatively recently. After (Sakao et al. 2009b), classification of the research aims are grouped into "PSS offer modelling", "PSS development process", and "PSS potential". The first two, i.e. offer modelling and development process, were basic aims of engineering design research, as presented in (Finger and Dixon 1989 a) and (Finger and Dixon 1989 b). Table 11.2 illustrates the aims of the research published in international journals.

Table 11.2 Classification of PSS design literature (journal articles)

Research aim	Before 2008	After 2009
PSS offer modelling	(Sakao and Shimomura 2007) (Aurich et al. 2006) (Dausch and Hsu 2006) (Östlin et al. 2008) (Alonso-Rasgado et al. 2004)	(Panshef et al. 2009; Sakao et al. 2009c) (Moon et al. 2009) (Doultsinou et al. 2009) (Maussang et al. 2009) (Hara et al. 2009) (Aurich et al. 2009)
PSS development process	(Alonso-Rasgado and Thompson 2006) (Morelli 2003) (Aurich et al. 2006)	(Sakao et al. 2009a) (Doultsinou et al. 2009) (Maussang et al. 2009) (Molloy et al. 2009) (Kimita et al. 2009) (Sundin et al. 2009)
PSS potential	(Evans et al. 2007)	(Azarenko et al. 2009)

Note: Some articles had several aims to the research but have been classified by the main aim.

11.2.3 Future Research Issues

According to a recent white paper on industrial PSS (Meier et al. 2010), “In 10 years the following statements will be relevant: Result oriented business models evolve as an industry standard. Complex development processes are simplified by automatic […] configuration by Plug & Play of product and service modules. Service will be provided globally by service supply chains based on modularized service processes.” A lot to research needs to be carried out in PSS design to realize this picture.

(Sakao et al. 2009b) further discuss research needed in PSS design, namely design process, organizational structure, and mindset.

Design process

More research is needed to support companies to successfully integrate product and service development. Methods, tools, and procedures should support providers to develop services that are economically and environmentally beneficial, and they need to be tested and validated in firms. Several concepts and suggestions (e.g. Sakao et al. 2009c, Sakao and Lindahl 2009) should be incorporated into research; followed by empirical testing.

Organizational structure

The organizational structure needs to change in a company. More specifically, how to organize the company according to the services offered is one area where more research can be performed. Part of this is the competence profile of the company, which needs to shift when moving into services (for example, more service technicians or more business and service developers would likely be needed). A logistical system and a remanufacturing system may also need to be developed.

Mindset

Companies need to undergo major changes in their mindset. Companies that have a strong culture and pride in their products also have to build trust, and their employees need to believe in their services. Services also need to have a high status and be incorporated into the company. The importance of mindset and how it can be built up in line with new company values will be an interesting re-search area.

11.3 Integrated Development of Technology and the Business Model

11.3.1 Implication from Theory

As described in the introduction, companies in developed countries face severe competition. Therefore, innovative solutions are demanded in order for them to be competitive. To do this, their products may need a fundamental change that requires technology development. Technology development would be an interesting issue to consider if engineering design was expanded and further developed. The material is chosen based on the product, which depends on the system, assuming a given technology. Technology development is conducted before traditional engineering design begins; it has not been addressed as the focus of engineering design.

Therefore, addressing technology development as a part of expanded engineering design could be an interesting challenge. This becomes more interesting when considering that designers have more freedom earlier in the design process. In addition, the stage of technology development is important to innovation, which is an especially important issue in economic growth.

The business model, rather than the organizational structure of a firm and service activity provided within the scheme, has the biggest impact. This is depicted by figure 11.2 and has been named the “V-shape in techno-business”. This allows the positioning of different disciplines. PSS design addresses both ‘hard’ and ‘soft’ is-sues and has a higher impact, while traditional product design deals with the physical product, including its materials. “Integrated development of technology and the business model” has the highest impact. The length in the horizontal axis for each depicted area can be interpreted as the degree of freedom in design.

Longer time to market is characteristic of technology development (e.g. Tatikonda and Rosenthal 2000) and has greater uncertainty compared to traditional product development. This is where services can be an effective way to de-crease the impact of uncertainty. When a product with a new technology is launched, it can be combined effectively with a service as a package that takes care of technical risks.

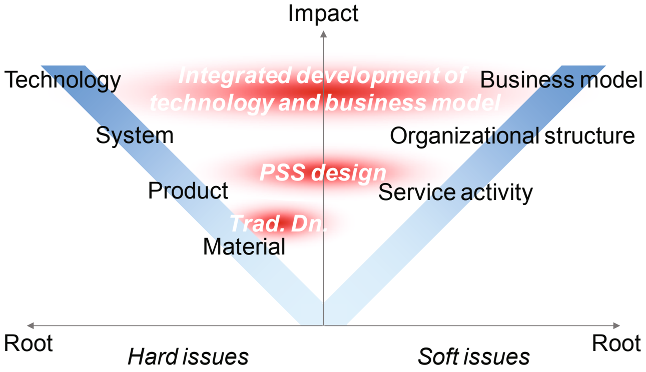

Fig. 11.2 V-shaped relation in techno-business space. “Trad. Dn.” means traditional product design

11.3.2 Industrial Needs

A driver for industry is pressure to decrease time-to-market generally. Emerging opportunities in the markets of developing countries is a particular driver. This is related to time-to-market, because current market opportunities may be lost without quick action. There is a need to implement new technologies for emerging markets, especially in the sector of environmental technologies. Developing countries, such as China, Russia and India, have a great need for solutions with environmental technologies to decrease their environmental impacts. In these situations, investigating alternative business models can be effective, because combining services in a different business model could decrease time-to-market. For instance, a lot of Swedish firms have environmental technologies to potentially sell to the emerging markets, but building up a business model appropriate to the solution required is an issue (Swentec 2009).

11.3.3 Existing Knowledge and Research Opportunity

In previous research on integrated product development, Drejer highlighted the need to integrate product and technology development that originates from the customers' requirement of shortened time to market (Drejer 2002). Looking closely at technology development processes in the automotive sector, it is argued that technology development should happen before the requirement analysis for a product, because doing it the other way around takes more time and cost (Ueno 1995). The technology developed is tuned after the requirement becomes available. An information processing model has been proposed to represent the process of developing products based on novel technical capabilities (Iansiti 1995). The process begins with exploration of the technological alternatives, and then moves to integration into a technological concept. Development of a detailed system and, then, production then occurs.

Drejer has argued for the need to integrate different disciplines, such as technology and sales (Drejer 2002). Nyström demonstrated the need to address both marketing and R&D strategies within product development, and provided a framework for characterizing and integrating marketing and technology strategies (Nyström 1985). Another framework containing one line for business gates and another for technical decisions for a new product development process has been proposed, based on good practice in the chemical industry (Shaw et al. 2001). However, this framework does not address the design of a business model. (Efstathiades et al. 2002) discuss integrated process plans for implementing technologies, but do not focus on business models either.

Previous research in the PSS area has shown that the business model is an important factor (e.g. Mont et al. 2006). However, its integration with 'hard' issues (i.e. product or technology) has not yet been discussed thoroughly. This is where research is needed: the integration of technology and business development. This integration is important as they influence each other, for example, a technology difficult or unfamiliar to users requires an intimate support service, from which a provider would like to profit.

Theoretical engineering knowledge in this area is insufficient, and there appears to be little systematized knowledge. This is not surprising, since the development of theory for the design/development aspects of PSS only began in the last decade. Utilizing new technologies to develop PSS has not been explored.

11.4 Conclusion

Following the introduction of the three dimensions, this chapter described the future research issues of PSS design: offer, customer/user, and provider. Future research issues were classified into design process, organizational structure, and mindset. Integrated development of technology and the business model was proposed as an interesting research area, following PSS design, because it has the potential to have a large impact on performance, is demanded by industry, and there is little knowledge in this area in the literature.

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Chapter 12
Open Product Development

A. Riitahuhta[1], T. Lehtonen[1], A. Pulkkinen[1] and P. Huhtala[1]

Abstract Open Product Development Methodology is the future of design methodology. It contains three phases:

1. Proactive, strategy-based construction of product development knowledge
2. Fast, efficient product development utilising the right resources
3. Guarantee of product life-cycle knowledge.

Each phase has its own methods, of which the following are presented in this chapter: Company Strategic Landscape, Product Family Design and Configuration Process, and the Combined Variation of Product, Manufacturing Processes and Networks. It is important to strengthen the head designer's role and that the Product Architect takes new responsibilities in design, such as in the environmental review stage.

12.1 Introduction

Why does design methodology exist? Industry requested the International Conference on Engineering Design (ICED) conference in 1997, organised by this research group, with its theme *World Class Products by World Class Methods*. Later, in the Workshop Design-Konstruktion (WDK) meeting in Rigi, Prof. M. M. Andreasen presented an analysis of the scientific research and questioned whether the Design Research Community was capable of responding to the challenge of the conference theme. Is the community able to create methods to help develop world-class products? Several other researchers have expressed doubts over the industrial usability of design methods, and opinions on how methodology usage can be enhanced (Birkhofer 2005). Despite these questions, this research group believes the theme of the conference, World Class Products by World Class Methods, is the rationale for future design methodology. The group has developed the theme in the following way:

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Table 12.1 From machine element-centric design towards Future Design Methodology

Description	Theory, method, tool
Design of a gear box, clutch, and instruments	Machine Elements
Vehicle design	FEM, Machine dynamics
Improved systemisation of power plant design	Pahl & Beitz method, VDI2221, VDI2225, Integrated Product Development
Development of parametric 3D design	Pahl & Beitz
Expert system of engineering configuration for process plant design	Model-Based and Object-Oriented Knowledge representation, Theory of Technical Systems
Modularisation, Platforms, Configuration	Theory of Technical Systems, Product Structuring, Design for Configuration
Dynamic Modularisation, Product Life-Cycle Management, Change Management	Design Science, Theory of Technical Systems, Product Structuring
Conceptual_ DFMA, Optimisation of Variation and Flexibility of Combination of Product, Process and Network	Integrated Product and Production Design, Matrix Methods, DFX, DFMA,
Innovation, Radical Innovation, Incremental Innovation	Radical Innovation by Design (RID), Incremental Innovation method for multidisciplinary product
Simulation-Based Design, Early design combining Simulation and TRIZ	Parametric Design, TRIZ
Verification & Validation	Set-based Concurrent Engineering, Systems Engineering
Strategic-Based Product and Production System Development	Company Strategic Landscape
DFMA	C_DFMA, Augmented assembly, Virtual Reality

As seen in the table, consolidated co-operation with industry creates a need to add new subjects to the method collection. A single method alone cannot meet the need. The aim here is to consolidate the group's research. A Future Design Methodology is constructed, which includes elements from Table 12.1. The methodology is partly speculative (the wholeness of the methodology); however, the parts from the table are tested scientifically and by industry. The methodology is the vision of 30 academic and industrial researchers who are developing and testing it. The focus area here is highly diverse products and services.

Many reliable theories have been created by Design Society Scientists; some of them are presented in Table 12.1. However, some methods are partial additions or merely elaborate details. Occasionally, these additions blur an originally clear method. The Design Research community has been attempting to consolidate methods but results of the consolidation remain minor.

In the methodology here, the aim is to develop different levels and avoid overly complicated, highly detailed methodology.

12.2 General Design Theory

The design community has produced several methods and observations on design. The following terms are in general use when describing design: Multi-disciplinary, Collaborative, Product/Service, Sustainable, Innovative, Globally distributed, Life-cycle oriented, Multi-cultural. The following aspects of Design Methods are presented here: Evaluation, Architecture, Business care, Mission, Technology infusion, Design knowledge, C_DFMA, Verification & Validation, PLM, PDM, Change management, , Simulation-based. Historical, implementation, designer, management, quality, corporate and strategy perspectives will be elaborated. Business literature has introduced several views on innovation, production paradigms, management, and design-related methods, such as QFD and Mass Customisation.

Grabowski et al. began developing General Design Theory (GDT) in the late 1990s. Yoshikawa presented in the keynote speech in International Conference on Engineering Design, 2010 that he is continuing the development of GDT. In the industrial sector, Toyota and its academic partners developed systems that integrate product and production. General theory was developed in the Intelligent Manufacturing Systems (IMS) program, for example, the Post Mass Production paradigm. Participation in the IMS programme, by developing an Engineering Design configuration, was a great way to integrate the research results into other worldwide knowledge management research. The IMS programme presented several Open Innovation principles (ISM 2010).

The C_K method is constantly developing; learning it is at an early stage in the Design Community. Weber (Weber 2010) presented a method for consolidating the main features of Axiomatic Design and Domain theories. Prof. Birkhofer's group has developed an integration tool that offers an accurate method using the criteria chosen.

General Design methodology has not yet been developed. Despite this, new features for designing methodologies have been developed, e.g. the business view.

12.3 Future Design Methodology

According to the reasoning above, the implementation of a method assumes an understanding of why a methodical design is useful, and knowledge of general, common principles of design methods. Product Development is divided into several methods for the different phases. Pahl & Beitz state that there are the following phases:

- Product Planning and Clarification of the Task
- Conceptual Design
- Embodiment Design

- Detail Design

The research group surveyed what kind of design methods world-leading companies in the mobile machinery business are using. From the interview results, an ideal Product Development (PD) methodology was synthesised with companies' top management. According to these ideal methodologies, companies would start by defining the Business Case, then in the second phase, focus on Technology Development (Figure 12.1). The emphasis on these two phases is the central finding of this research. Business importance and new technology infusion occur earlier than in design methods. The Mobile Machinery Product Development method created also includes knowledge management and extensive simulation with commercially available tools (Riitahuhta et al. 2005).

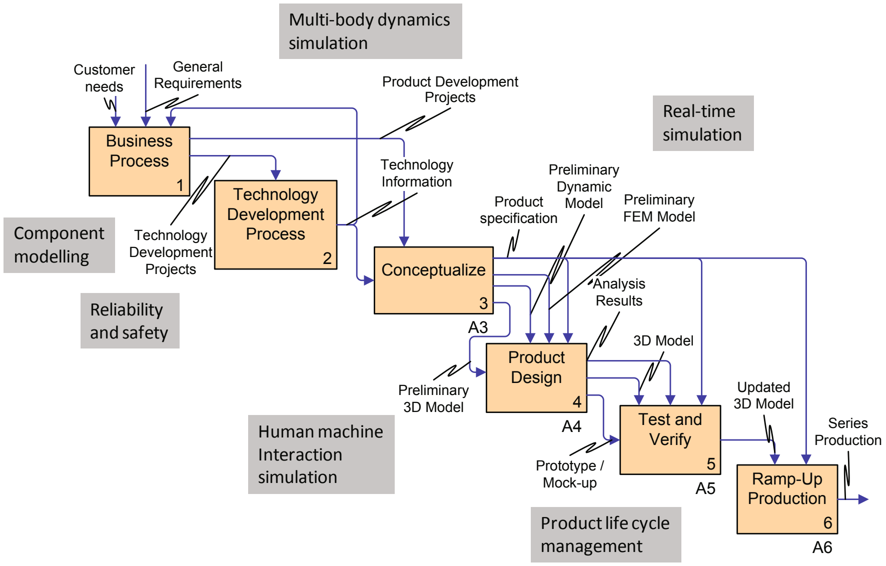

Fig. 12.1 MMPD Mobile Machinery Methodology. The iteration between phases is not presented in the figure even though it exists in similar ones (Riitahuhta et al. 2005)

Based on this research, PD methodology has to integrate with Business processes.

An academic-industrial collaboration has been formed as a group called RRG. Its agenda is to create Design Science, support research and industrial working results of members, and, at the highest level, enhance the world through Design Science. There are 30 members: four doctors in universities, five doctors and five R&D directors in industry (Nokia, Konecranes, Wartsila, Sandvik, Metso), and PhD students in academia or placed in industry. The RRG group has started clustering its design research and visioning Future Design Methodology.

Industry has recently claimed that the methodology should include an Open Innovation principle (Chesbrough 2003). However, Open Innovation is mainly used in software and internet businesses. Its introduction to businesses where physical product has an important role, for example, mobile machinery, is weakly promoted. The group's vision is to strengthen the understanding of openness, based on the paradigms of Intelligent Manufacturing Systems and the strategic development of the Open Innovation Strategy and Policy Group (OISPG) in the EU (OISPG 2010). Openness in PD collaboration will happen using social media, e.g. crowd sourcing, in design. Some early results have been achieved and presented on the design that the group has created (Taloussanomat 2010). The biggest problem is verification of results. The group has participated in university studies on Open Innovation in the cooperative education model called Demola, which received the European prize, Regional Innovation Award (RIA) (Assembly of European Regions 2010).

RRG has named the Future Design Methodology 'Open Product Development'.

Industrial application shows that methods applied at the operating level have to be very clear and visually understandable for management decision-making and yet permit deep study by experts, for example, the stage-gate model presented by Cooper (Cooper 2001), which is widely used in industry, even in SME businesses. Decision-making is realised in predefined gates. The information needed is in a similar format every time. However, information creation assumes detailed working by experts. Many well-known methods will be utilised at the industrial operation level. The research group continues its research on selected methods and applies results from the research community to Open Product Development (OPD).

In OPD there are three main areas:

1. Proactive, strategy-based construction of product development knowledge
2. Fast, efficient product development utilising the right resources
3. Guarantee of product life-cycle knowledge.

Suitable methods for each area have been developed. The main areas, corresponding methods and industrial cases where methods have been verified are presented in Table 12.2.

Table 12.2 Open Product Development methodology: Main areas, suitable methods, and the area where the method is mainly created.

Main areas	Method	Case
Proactive, strategy-based construction of product development facilities	CSL- Create Company Strategic Landscape	Marine industry branch platform
Fast, efficient product development utilising the right resources	CFD- Start Product Family Design and Configuration Process	Process plant design
	VUP- Start Verification and Validation Process	Consumer electronics

Table 12.2 (continued)

Main areas	Method	Case
	KONTU- Combined Variation of Product, Manufacturing Processes and Networks	Mobile Machinery
Guarantee of product life-cycle facilities	Global Processes for High Variant Products	Multi-technical Products

In the table, the methods follow each other. In reality, the methods are used in the order appropriate to the situation.

A new role in design offices, Product Architect, is suggested to realise OPD's three main areas. The inspiration for this is from world-renowned architect Alvar Aalto, who presented on the responsibilities of regional architect.

Aalto defined architecture as an idea that a building has to be created for occupants, and that it considers their physical and psychic affluence as being as beneficial as possible in relation to the environment; concurrently, the environment has to be kept totally in balance. Aalto also stated that regional planning, which consists of people who completely manage all stages of architectonic structural design from regional town planning down to the smallest building's technical detail, has to impart to expert groups. A building's appearance and style are not disengaged parts of the socio-technical construct of building. Aalto emphasises an abode's biological aspects of design. Social responsibility and engineering innovation form important parts. Assignments are very similar to that which Birkhofer presented on the use of systematic design methods in industry (Birkhofer 2005).

Architecture is what architects produce; they also help clients make decisions about product systems. It is important that business management understands and manages the main areas in Table 12.2. Top management has to guarantee the facilities needed by the Product Architect, e.g. dedicate resources. Top management does not need to manage specific methods, except the R&D director, whose management is included. The Product Architect manages all the methods in Table 12.2; on the next level, designers might use detailed methods. OPD is visualised in figure 12.2. The three main areas are described as phases. A Product Architect works in all phases. Designers work in their speciality areas. Arrows in figure 12.2 describe the iterative nature of design.

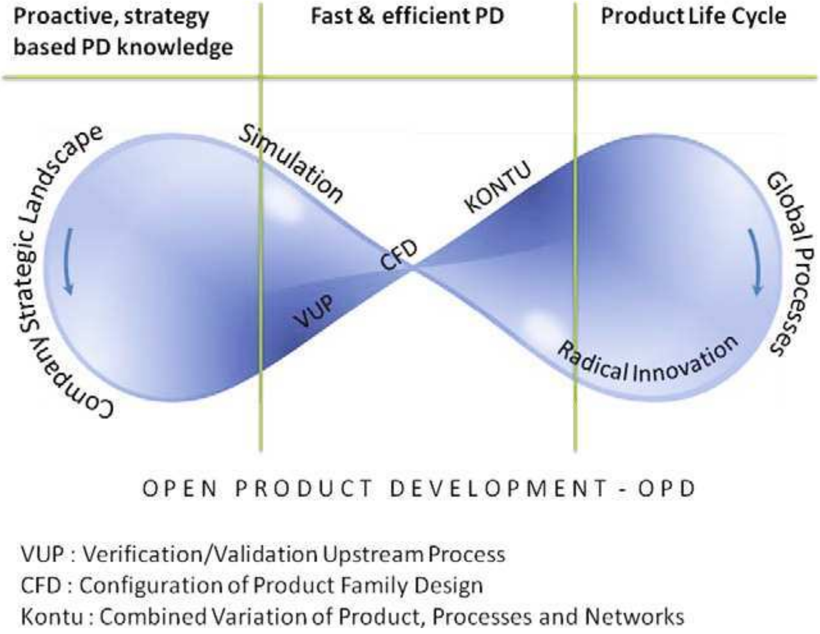

Fig. 12.2 Open Product Development methodology

The following sections describe the methods in Table 12.2. The research group has published dissertations and academic papers on these methods, which have been tested and validated in industrial use.

12.3.1 CSL- Company Strategic Landscape

The framework model – Company Strategic Landscape (CSL) (Lehtonen et al. 2007) – defines the elements related to product development operations and company production. The figure below shows which relations between these elements are dominant, and thus important. In research that aims to develop operations, efforts must be directed at the management of the guiding relations, as these will guide the entity. Elements related to funding (investment capitals, etc.) are not included in the figure.

The CSL framework model describes the key issues in the structuring of the product and the relations between them. The product structure is in the top left corner. In this figure, the ‘structure’ of the product does not refer to the assembly structure and a list of parts, as a product assembled of the same parts may be divided differently by product structure management. The structuring of the product is guided by the structuring of the value chain in which the product must operate. On the other hand, the properties of the product structure enable and limit the number of possible value chains. The value chains, in turn, are determined by business goals (the structuring of the strategy).

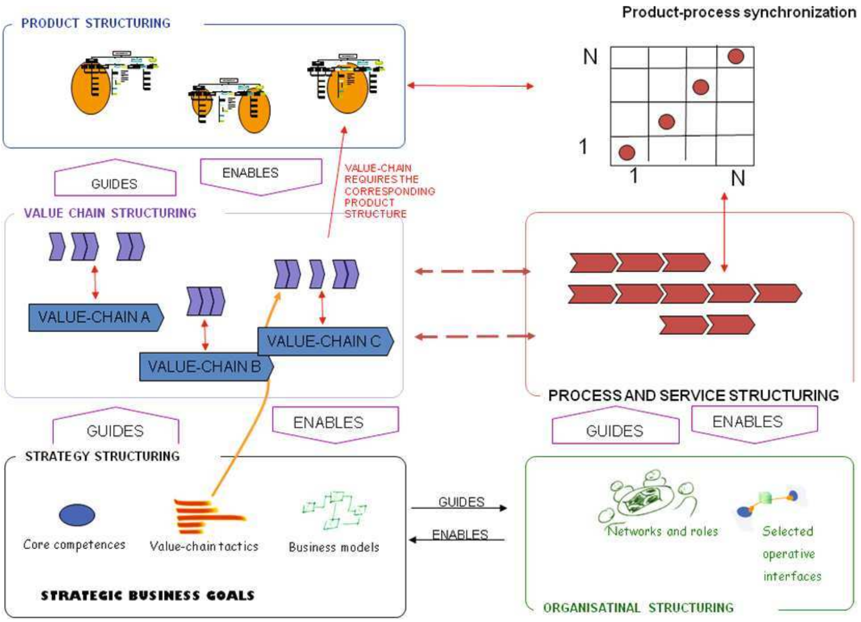

Fig. 12.3 In the Company Strategic Landscape framework, business operations are seen as an entity

The sales, design, and production processes of the products and services to be delivered are shown in the middle on the right-hand side. The structure of the internal resources and the network (the structuring of the organization), and the selected methods (operative interfaces) are shown in their background. The structuring of the organization and the business goals exist as a reciprocally guiding and constraining relationship.

The key idea in the CSL framework model is the relationship between the internal structure of the product and the delivery process. In principle, the product structure and the delivery process can be selected separately. They are usually examined one at a time while using the other as background data. When optimizing operations, these two are no longer seen as separate but must be synchronized. The points in the figure in the top right corner indicate the product structure/delivery method pairs that are "good points" or combinations in which operations are carried out rationally according to the *selected goal*. In the figure, the points are located on the diagonal line merely as an example. The points do not necessarily form an unambiguous vector – good points are not necessarily found.

The ability of the delivery methods to support the set *goals* varies drastically. In interpreting the figure, a design process defines the product structure, which supports set goals. The product structure, in turn, only enables the value chains that only correspond to certain business goals.

12.3.2 DFC- Product Configuration

Configuration, like design, has two meanings, one of which refers to the activity and the other, the object, the result of an activity. Here, activity is defined as a configuring or configuration task. The object is defined as a product configuration, i.e. representation of an individual product.

A product configuration consists of a group of components and their relationships. It is a special arrangement taken from a set of possible arrangements, which compose a configurable product family. The specific characteristics of a specific configuration enable the properties required by a specific purpose. However, the purpose is similar to the purposes of configurations of the product family, e.g. the purpose of the long-range and cargo configurations of an aeroplane are generally related.

A product configuration is derived from a predefined set of design units, such as building blocks, parts, modules, and assemblies, by relating the design units (Brown 1998). In addition, the ways of relating the design units have been previously defined. Yu characterizes the configuration task: "*From [a] given set of elements, to create an arrangement by defining a set of relationships between selected elements that satisfies the design requirements and constraints*" (Yu 1996). Configuring is typically computerized by specific software, namely a configurator. The previously specified and documented knowledge on configurable product families is stored in the knowledge base of the configurator and used repetitively in the task.

The task of product configuration may be carried out by the sales or engineering functions of a company. The early adaptations of product configuration date back to the 1980s, when a variety of expert system technologies were adopted to define customer specific products, such as computer systems and power plants (Riitahuhta 1988, Barker and O'Connor 1989, Sviokla 1990). Since then, the research issues related to product configuration have ranged from knowledge engineering conceptualizations (Sabin and Weigel 1998, Soininen 2000) to the application guidelines of configuration techniques for enhancing the utilization of modularity and product families (Riitahuhta and Pulkkinen 2001, Hvam et al. 2008). Hence, product configuration technology has evolved from the pioneering cases of early adopters to maturity, which is represented by the growing number of vendors and applications installed.

Sviokla (Sviokla 1990) reported that Digital equipment corporation estimated savings of about 15 million USD during the first five-year period of using the

XSEL/XCON system. The estimated fourfold increase in configuration personnel was avoided, task performance at least trebled, and management and distribution of configuration knowledge was standardized and enhanced. Moreover, the quality of order processing increased, i.e. instances of correct configurations rose from 65 - 90% to 95 - 98%. Two decades later, Hvam et al. (Hvam et al. 2010) studied four cases of product configuration and reported similar improvements. For instance, they found that lead times in making quotations and Bills of Material (BOMs) and routings, as well as the resources used in making the BOMs, were reduced to one tenth or less. At the same time, the timeliness and correctness of specifications rose. Product configuration has had noteworthy indirect effects on the standardization of items, formalization of engineering knowledge, increased sales and customer satisfaction, diminished production costs and total lead times. However, the sustainable adoption of configuration and harvesting of the indirect benefits require the alignment of business processes and organizations with product structures and IT support (Pulkkinen 2007).

12.3.3 Kontu: Combined Variation of Product, Manufacturing Processes and Networks

To clarify the concept of variety in products, processes and networks, as well as their relations, a research project is being carried out at Tampere University of Technology (TUT). The project focuses on variety and its effects on processes and networks. In product variety, the aim is to recognise the generic types and measures of variety in product structures that cause variety in processes and/or networks. The issue is defining the characteristics of product varieties that indicate the variety from the aspect of the process or network. The type and measure of variety, as well as its position within the value chain, have an effect on the severity of internal variety.

The research emphasises three dimensions: the variety and standardisation of solutions in hierarchies of product structures within a product family; the use of similarities between product families; and production processes. The project aims to develop a methodology for finding the similarities between families, standardisation within families and developing the generic structures and architectures, as presented by Harlou (Harlou 2006) for products, but also for production processes, systems and networks.

It is important to recognize the variety within an existing product family and the effects that that variety has on the production systems and processes. The aim is to recognize the products that are of customer interest and to find similarities and differences within product families. This product-based view is supported by the process-based view, where products are approached from the production angle. In this context, the foundation of the product family changes and the composition of the family will vary greatly.

The similarities between product families can be utilized in product design engineering, production and supply in many different ways. The product family is composed of a different set of objects in each of these. The results of development should be found in the generic structures and architectures of product families, and harvested in standardised processes, which will lead to productivity increase overall.

12.4 Conclusions

Design methodology for highly variants products was the focus of this research. Verification and validation methods are developed in the electronic consumer product development sector, where series are huge and variants exist.

A Future Design Methodology, Open Product Development (OPD), is proposed. OPD is as follows:

- Basic structure and visualisation of the methodology is clear and simple but allows thorough working by an expert, due to the design
- Business drivers and constraints have an important role in the methodology
- Methodology supports design of product families
- Governing properties of design are knowledge management, variation and lifecycle management, optimisation of manufacturing processes and networking, and quality management through verification and validation processes at the design stage
- Efficient methods of Incremental and Radical Innovation and their use are created by the methodology
- Roles and responsibilities of the design director and product architect are applied from best practice in architecture.

OPD's methods have been developed, verified and validated by the research group. OPD totality has been assessed in the group's research work and using industry experience. The goal is to consolidate OPD, utilising Design Society research.

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Chapter 13
Managing Virtual Product Creation

R. Anderl[1]

Abstract Design methodology is the backbone of Virtual Product Creation (VPC). The methods implemented in application software systems to support engineering to develop innovative products are embedded in design methodology. A product creation process as a complex iterative decision process needs appropriate management techniques.

Common approaches are required to plan, execute, monitor and evaluate product creation activities. Requirements of project management, quality management and innovation management also have to be fulfilled. All activities of Virtual Product Creation have to be integrated into product creation workflows.

This chapter discusses major management approaches, such as lifecycle management, workflow management, progress monitoring, and maturity management, as complementary to design methodology.

13.1 Introduction

A virtual product creation process is an iterative decision process using information and communication technology to engineer the appropriate product solution. Virtual product creation is strongly influenced by design methodology (as described in VDI guideline 2221) that promotes a continuous decision process, developing a product from requirements definition to a completely described product solution prepared for production. This decision process produces intermediate product solutions from an abstract function-based product description, passing through phases where further concretization is performed, to a fully described product solution. During this iterative decision process, results of the phases are developed and stored.

Information and communication technology contribute to virtual product creation through three major technologies: application software systems, digital representation of development results, and powerful communication technologies.

Application software systems support:

- product modelling using parametric and feature-based CAD systems

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- analysis, simulation and optimization using FEA (Finite Element Analysis), MBS (Multi Body Simulation), and CFD (Computational Fluid Dynamics)
- virtual validation and verification using DMU systems (Digital Mock-Up systems)
- rapid prototyping through virtual (e.g. Virtual Reality systems) and physical prototyping (RPT, Rapid Prototyping and Tooling systems)
- consistent use of product data in subsequent process chains (CAX process chains)
- the mapping of organizational and workflow structures into product data management systems (PDM) to allow controlled and authorized access to product development and design results via mouse click.

The digital representation of development results is based on the integrated product data model, which is based on ISO Standard 10303 "Product Data Representation and Exchange", and enables:

- harmonized and standardized data representation
- consistent product data definition through administrative and organisational identification
- seamless flow of digital data between application software systems
- integrated representation platform for deriving downstream data generation, e.g. for product presentation in technical product documentation.

Powerful communication technologies are provided through:

- fast information access to sources worldwide, based on internet technology
- application software integration, based on communication protocols supporting the service-oriented software architecture (SOA)
- collaboration protocols supporting web portals and audio as well as video communication.

Information and communication technologies are developing rapidly, as demonstrated in Web 2.0 functionalities. The influence of information and communication technologies is perceptible in virtual product creation. Stronger integrated application software systems are covering more and more phases of the product creation process. The penetration of product development processes by digital information flows is growing and becoming increasingly mature.

As virtual product development methods are being used on a frequent basis, the organisation of the virtual product creation process has gained strategic importance. A basic approach for organizing virtual product creation is to understand the product lifecycle and to manage allocated workflows accordingly.

13.2 Lifecycle Approaches and Workflow Management

A lifecycle concept is a way of providing a holistic view of a complex time flow, dedicated to an object of interest and to categorising and structuring the necessary actions. Lifecycle concepts are typically characterised by three criteria:

- The holistic approach
  The holistic approach provides an overall understanding of the complex time flow of the object of interest. When the product is the object of interest, the holistic approach supports a top down analysis of the product's time flow from cradle to grave, from requirements definition to its recycling or demolition.
- The categorisation approach
  Lifecycle approaches are typically categorised into phases that are embedded in a lifecycle phase structure, that is, a sequence. Each phase is characterised by workflows, including sets of activities. Activities are basic constructs that transform input into output and are used as major constructs to define workflows.
- The cycle approach.
  The cycle approach indicates the desire to feed end-of-life results back into a start-of-life phase of the successive lifecycle.

Lifecycle concepts are a major way to structure processes, particularly processes related to products. Product lifecycle concepts depend on their purpose and aim for a detailed understanding of the processes under consideration to enable their planning and controlling. Typically, three major purposes are of interest to product lifecycle concepts:

- Business administration
- Ecological sustainability
- Information technology.

The business administration focus in a product lifecycle concept is positioning and evaluating a product in the market. Thus, the focus is product success in the market. Typically, 5 phases are defined: the introduction phase, the growth phase, the maturity phase, the saturation phase and the decline phase. Each phase is characterised by quantified business ratios, such as revenue, cost and profit. A product is allocated to a lifecycle phase according to its business ratios and their extrapolation. This then enables strategic decisions, for example, pushing for product development (Cox 1967) (Scheuing 1969) (Staehle 1999).

The focus on ecological sustainability distinguishes between information flow and material flow phases (Dannheim et al. 1997) (Birkhofer and Grüner 2002) (Abele et al. 2005). Information flow phases represent product creation phases, such as product planning, design and production planning, while material flow phases are a holistic sequence of phases, from raw material extraction through production, and from product usage to recycling and demolition. Information flow and material flow phases are positioned orthogonal to each other. The production phase is understood as the phase where information flow meets material flow and controls production. The main idea of this lifecycle concept, however, is to feed knowledge from material flow phases back into information flow and design phases to improve ecological sustainability of the successive product.

The information technology focus is seamless digital information flow throughout the product lifecycle phases. For this purpose, seven lifecycle phases have been defined. These comprise product planning, product design, production planning, production, product marketing and distribution, product usage, and product recycling and demolition. Following the method of consistently using product data in successive product lifecycle phases, the concept of the integrated product data model has gained international importance. The basics are described in ISO Standard 10303 (Product Data Representation and Exchange), which has become known as STEP (Standard for the Exchange of Product Model Data) (Anderl and Trippner 2000).

The lifecycle focus driven by information technology is of major interest in the management of virtual product development as it is a sophisticated approach to defining workflows, as well as planning and control methods.

13.2.1Information Technology-driven Product Lifecycle

The product lifecycle approach driven by information technology structures the product lifecycle into 7 phases that include product planning, design, production planning, production, product marketing and distribution, product usage, and product recycling and demolition. The first three phases are classed as product development, and the first four, product creation. Figure 13.1 illustrates the information technology-driven product lifecycle approach.

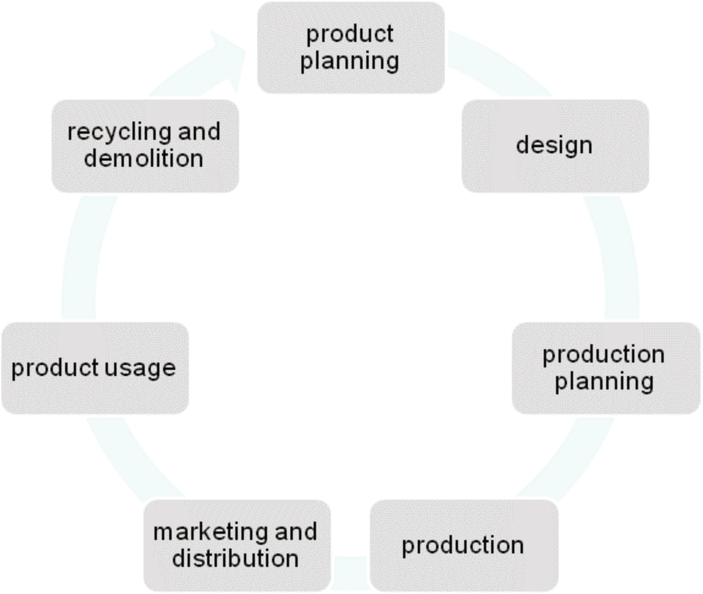


Fig. 13.1 Information technology-driven product lifecycle

Within the product creation phase, workflows are identified to enable integrated sequences of activities that interact with each other (Anderl et al. 2009). The two major workflows are product development and production planning, which are typically supported by simultaneous engineering methods. Besides these, a number of complementary workflows need to be established. Such workflows comprise the integration of product modelling with analysis, simulation and optimization, as well as product verification and validation. These complementary workflows are typically implemented as process chains, such as CAD-FEA (finite element analysis), CAD-MBS (multi body simulation), CAD-CFD (computational fluid dynamics), CAD-DMU (digital mock-up) and CAD-VR (virtual reality).

Besides these workflows based on seamless digital product data flows, other important workflows gain in importance, such as the workflows for the integration of physical prototyping and testing, i.e. CAD-RPT (rapid prototyping and tooling). Figure 13.2 illustrates workflows attached to product creation.

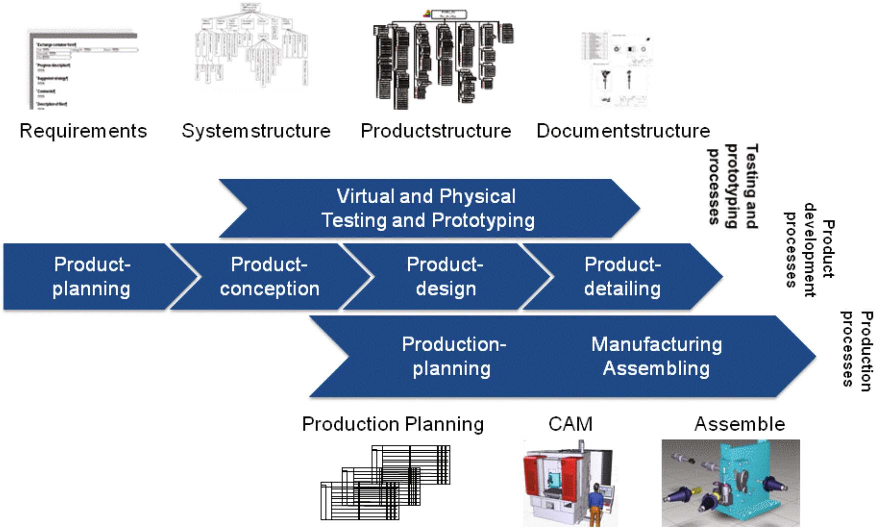


Fig. 13.2 Workflows for product creation

A closer look at the workflows indicates that they consist of interdependent activities. Activities might be organized in a sequence and be hierarchically structured; the workflow might be branched, synchronized and merged. A further important feature of workflows is that product data and engineering expertise has to be attached to the activities.

13.2.2 Workflow Management

Methods for workflow planning and control are required when using workflows in virtual product creation. These methods are typically implemented in PDM systems. Figure 13.3 shows workflow planning activities, workflow analysis, workflow modelling and workflow simulation, as well as the workflow activities control, execution and documentation.

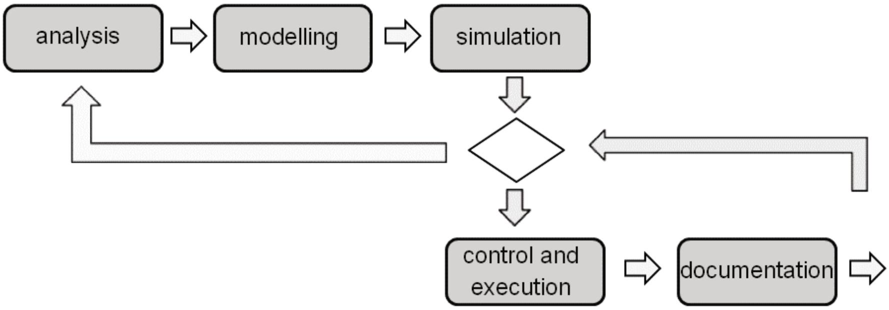


Fig. 13.3 Workflow planning and workflow control

Workflow planning creates methods for workflow analysis, workflow modelling and workflow simulation. Workflow analysis methods are typically used for analysing existing workflows and defining new workflows. Methods such as eEPC (enhanced Event-driven Process Chain) (Scheer 2000) are used. Workflow modelling methods aim to implement the appropriate activities and their structural composition to define the required workflow. Workflow simulation methods are dedicated to verifying and validating defined workflows through systematic walkthrough simulation.

After verification and validation, workflow control is initiated that allows the monitoring and supervision of workflow instances. During product creation, some workflows can be defined precisely, such as release management and change management. Many other workflows, however, might only be defined on an abstract level in order not to hinder creativity, flexibility and inspiration.

Workflow management systems are typically integrated into PDM systems and are dedicated to managing the progress of product creation based on the enterprise-specific workflow organisation. Figure 13.4 shows an example of workflow management.

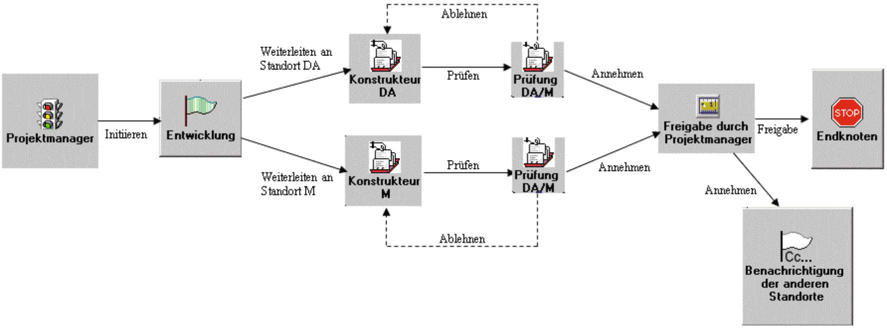


Fig. 13.4 Example of a workflow, based on the PDM system SmarTeam

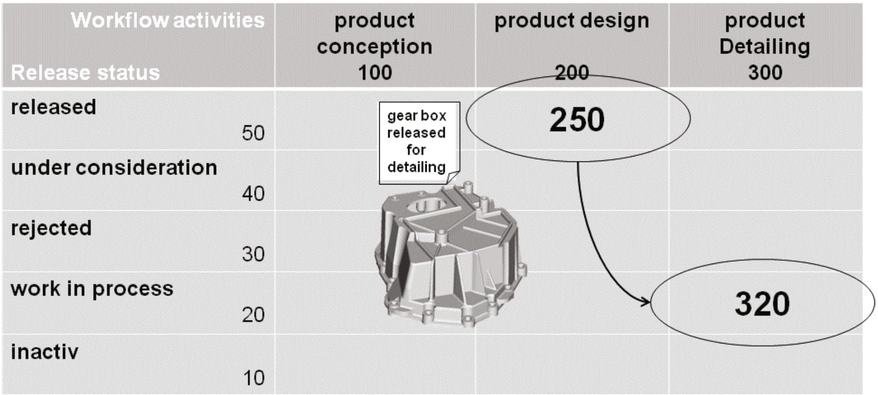
Managing workflows, however, needs appropriate organizational approaches that enable the monitoring and control of progress resulting from efficient and effective execution of the tasks assigned to the activities.

13.3 Progress Monitoring and Maturity Management

The results from completed workflow activities are represented as product data and are available as product models, e.g. digital 3D-CAD model, analysis, simulation and optimization results, as well as digital documents, e.g. technical drawings. Release management is an important issue in results approval (Eigner and Stelzer 2009).

Release management is based on an assessment and evaluation of the results and on a defined workflow. This workflow includes the assessment and evaluation of engineering and design results. After the quality and performance of engineering and design results are proven, they are released. Released engineering and design results are then approved for further usage. This means, however, that no further modifications are allowed. If a modification is necessary, a change workflow has to be initiated. It must clearly define proper migration from the released version of the engineering and design results to an improved version.

Due to the release of engineering and design results and the allocation of released results to workflows or product creation phases, the status of the product creation project becomes quantifiable. Interpretation of the quantified status of the product creation project gives an indication of the progress of the product creation project. To quantify the progress of product creation, progress indicators are required. Progress indicators can be generated by combining the workflow status (monitoring of workflow activities) with the release status (Figure 13.5).



Workflow activities Release status	product conception 100	product design ~~200~~	product Detailing 300
released 50		250	
under consideration 40			
rejected 30			
work in process 20			320
inactiv 10			

Fig. 13.5 Progress indicator generated as a combination of workflow activities and release status

Progress indicators are an appropriate way to monitor progress of the product creation project. While progress monitoring indicates which engineering and design results have been achieved and released, maturity management evaluates and controls the achieved results in the holistic context of the product creation project. Maturity management needs qualitative and quantitative conclusions to approve results achieved or to initiate required changes, which then have to be performed based on the appropriate change workflow.

A basic issue of maturity management is defining the completeness and reference level of quality of the product creation progress to enable evaluation. The completeness reference defines the set of results needed to declare an activity as being successfully finished and having achieved expected results. The reference level for quality is required to prove the value of the results and to stand tests. Therefore, methods for verification and validation are used. Verification reviews the achieved results against the profile of requirements while validation evaluates the achieved results for whether the purpose was fulfilled.

The integration of components and performance testing plays an important role in ensuring maturity. Integration of components includes the integration of supplier components. Physical prototyping and testing is crucial to integrate components and performance testing in the product creation process. The interacting workflows of virtual product development, physical prototyping and testing need to be considered.

13.4 Conclusion

Managing the Virtual Product Creation process is a highly complex challenge for industrial enterprises that requires profound concepts for appropriate organization of the sequences of actions. The conceptual approach described is based on the understanding of a product lifecycle approach driven by information technology. This approach structures the product lifecycle into lifecycle phases. Workflows are allocated to lifecycle phases and consist of activities that are combined and structured, based on key combination and structuring constructs. Engineering and design results are attached to workflow activities and have to be released for further usage.

The availability of engineering and design results enables the creation of further methods to measure and monitor progress in the Virtual Product Creation process. Progress monitoring may be used to enable maturity management that utilises the identification of the progress status and quantifies the maturity of the solutions of the product creation process.

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Chapter 14
Systems Engineering versus Design Methodology

U. Lindemann[1]

Abstract Systems Engineering, with its long tradition of success in dealing with complex systems, includes a number of methods and tools that are integral parts of Design Methodology. As research is an ongoing process, generating new results and insights, transferring and adopting further elements out from Systems Engineering has a lot of potential.

This will be demonstrated with some case studies of using matrix and graph methods to handle structural complexity. The cases deal with requirement analysis in a product-service system, knowledge exchange in practice, design to cost of mechatronic systems, and planning of material flow in a complex construction environment.

14.1 Introduction

Systems Engineering has a long tradition of large and complex projects in engineering and other domains. It covers a number of topics: requirement management, system design and project management. There are methods and tools related to change management, configuration management, modelling, simulation, reliability, safety, etc.

Many research institutes and teaching courses deal with Systems Engineering, but can usually only cover subsets of the whole range. Links between engineering design methodology and Systems Engineering have existed for several decades.

Currently, there is a shift away from focusing only on large projects, to a more general view of using the insights, methods and tools of Systems Engineering in a broader range of applications (INCOSE 2010).

In engineering design, there are a number of opportunities to foster the development of methods and tools by transferring and adopting Systems Engineering. Ongoing research is an indicator of further developments in Systems Engineering

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in terms of new requirements, changes in complexity and changes in our global community.

This chapter will focus on one specific aspect: structural complexity and the use of graph and matrix methods. This is of major importance when dealing with a fuzzy, incomplete and vague information basis, as is often the case in early phases of product development and engineering design in general.

Different levels of abstraction may be used, depending on the level of available data. In design, at least in mechanical engineering (as in civil engineering), there is a huge lack of data and information on requirements, boundary conditions and available sub-systems in early phases. Nevertheless, this basic information about structures can provide many insights for optimization or improvement of the system, or support for decision-making.

14.2 Structural Complexity

System Dynamics helps in modelling and analyzing complex structures. Don Stewart's basic idea of using a matrix-based approach, later called the Design Structure Matrix (DSM), was enhanced by Eppinger (Eppinger and Salminen 2001) and Browning (Browning 2001). They described the potential of optimizing these influence matrices by changing the order of elements within the matrix. They can then be used for modularization of a product (by clustering the matrix of product components) or the flow within an engineering design process (by triangularisation of the process elements in the matrix). Reordering matrices and, in addition, structural patterns that are indicators of specific situations, help to optimize systems such as products, organizations and processes.

Another type of matrix is the Domain Mapping Matrix (DMM), as discussed by Danilovic and Browning (Danilovic and Browning 2004), and well known as the core matrix within the House of Quality in the Quality Function Deployment method. Within this matrix, elements of two domains are mapped, for example, requirements and functions.

Maurer (Maurer 2007) suggested further steps. He combined DSM with DMM and aggregated them into the Multiple-Domain Matrix (MDM). This combination of matrices supports systems with a large quantity of dependencies, as they appear in practical applications. The MDM methodology fosters consideration of relevant dependencies and enables users to find adequate solutions. Another advantage is the improvement of quality in data acquisition. If, for example, the key question is about cooperation of people in a design department, people could be interviewed about their cooperation. With such an approach, the resulting answers will be of low quality. If, however, the dependencies between product parts are on hand (e.g. based on the BOM) and if the employee responsible for each part is known, the initially demanded matrix of dependencies between people (indicating their shared responsibility for product parts) can be computed. In addition, Maurer suggested using the equivalent benefits of matrix and graph representations of system dependencies. DSM as a strength-based graph proved to be an excellent tool for visualization (elements as nodes, dependencies as edges), which created an opportunity for additional analysis of structures.

Some key examples indicate the existing potential for enhancing engineering design, even in this small sector of Systems Engineering.

14.3 Requirement Analysis

The development of hybrid systems, including integrated services next to well-known hardware, is a highly topical issue in research and industry. The following example is part of ongoing research in an interdisciplinary group and is based on a paper about the structural analysis of requirements (Eben and Lindemann 2010).

The results of a structural analysis of the requirements for a hotel laundry service will be shown. The laundry service was developed to capture iterations between product development (e.g. of washing machines or planning software), service design (e.g. of delivery of laundry) and requirements management. The requirements and product properties have been systematically detailed, amended and refined.

Figure 14.1 is an extract of the graph representing an early version of the requirements set used to identify the meaning of structural criteria proposed in Table 14.1. An edge in the graph stands for "requirement has influence on requirement".

Table 14.1 Structural criteria for requirements (excerpt, Eben and Lindemann 2010)

Structural criterion	**Explanation according to Lindemann et al. (2009)**	**Meaning**	
nodes	directly or via possible paths	model or requirements, impact of its change.	Single nodes
Articulation node	Single node linking two subsets	The requirement links otherwise independent subsets of requirements. This requirement can for example represent an important interface or interaction in the regarded system.	
Start	Only outgoing relations	The requirement only influences one other directly, but it has a possible impact on various others via paths.	
Cluster	Subset of highly inter-connected elements with few links to elements outside	Requirements forming a cluster may belong to the same class, e.g. functional requirements (Eben et al., 2010) and be highly interdependent.	Subsets of nodes
Path	direct or indirect connection	Requirements connected via a path to a requirement affected by missing ones (Eben et al., 2010).	
Independent subsets	Subsets of nodes not linked by relations [Kreimeyer, 2010]	A subset of requirements having no influence on other subsets can be regarded separately, if no relations or other requirements have been neglected.	
Similarity	amount of	Requirement	

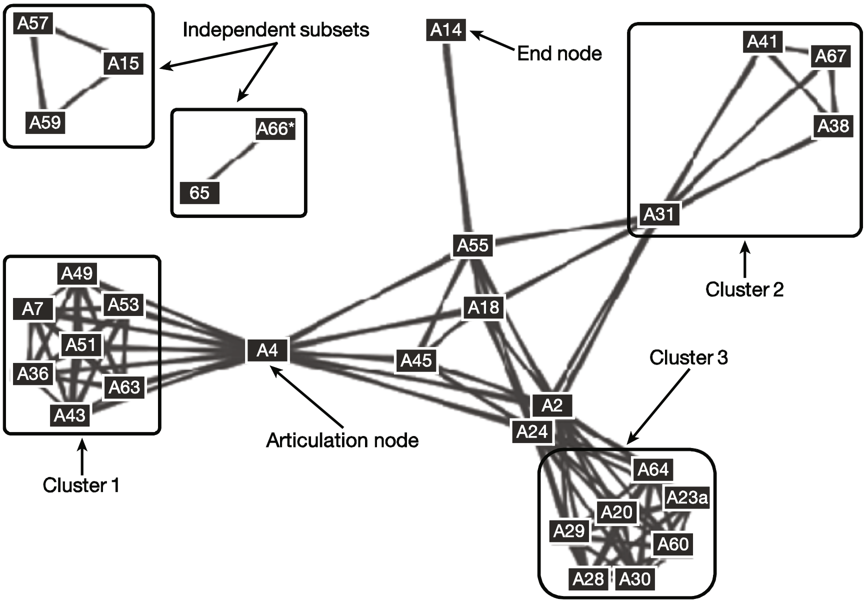


Fig. 14.1 Structure of the requirements for a hotel laundry service – an example

Table 14.2 shows some of the discussion on insights gained from the graph in figure 14.1.

Table 14.2 Critical discussion of the graph (figure 14.1) (excerpt, Eben and Lindemann 2010)

The requirement A14 "payment dependent on laundry amount" is represented by leaf node. It is obvious that this requirement has hardly any influence on the remaining system, as it is only dependent on the need for stock-keeping records (A55). Figure 14.1 depicts two independent subsets. First, there is a pair of requirements: A65 "monthly invoice" and A66 "minimum of profit margin". The requirements A57 "monthly report not containing staff data", A59 "invoice containing VAT registration number" and A15 "monthly report to customer" form another subset. Both requirement subsets concern the laundry service bookkeeping.

As both sets are closely related, links between them might have been missed. Thus, all the requirements have to be examined again to ensure that missed relations or requirements are identified. In this case, both sets are actually linked via an additional requirement: the contents of the monthly report. The articulation node A4 "delivery in time" links cluster 1 to the rest of the requirements. Thus, it can be seen that punctual delivery is highly dependent on the delivery times and management constraints defined in cluster 1 (A49 "delivery time towels", A51 "delivery time of bed linen", A53 "delivery time complete laundry", A36 "management of kitchen cloths", A43 "availability of planning software" A7 "correct management of cleaning process", and A63 "minimum amount of laundry for cost efficiency"). Moreover, A4 is an important interface with the remaining requirements. To handle the scheduling of delivery, the elements of cluster 1 have to be defined. The requirements of cluster 1 form a consistent group of process management-related items.

The examples described above indicate how structural criteria can be interpreted and how they support the analysis of requirements and decision-making in requirements management.

14.4 Knowledge Identification

In recent decades, many attempts have been made to foster knowledge management in practice, with the overall results being more or less disappointing. Looking at the demographic changes in most of the developed countries, and even some of the emerging markets, implicit knowledge and knowledge of dependencies is becoming more important. Even simple knowledge of the existence of colleagues, products and development stages is of major importance to the management of teams and their development during different stages of product development. For this reason, the isolated transfer of knowledge is not sufficient. Maurer, Klinger and Benz (Maurer et al 2009a) published the following results.

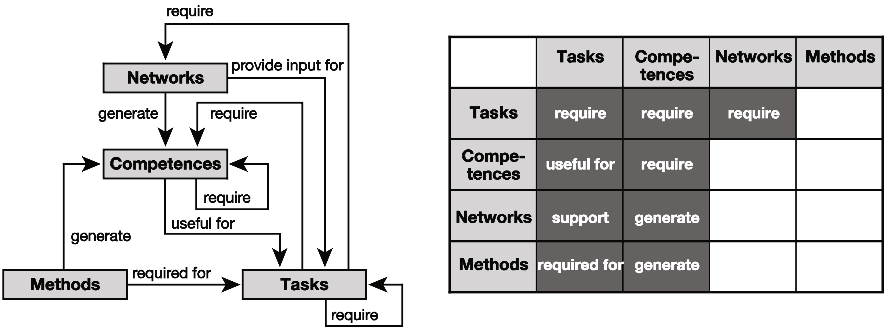
Experts possess explicit and implicit knowledge of important dependencies; this knowledge is difficult to communicate to other employees. The decisive dependencies and implicit connotations are neglected or get lost in a transfer process (figure 14.2, left).

Fig. 14.2 Transfer of knowledge, without considering dependencies, versus transfer of linked knowledge components

Methodical knowledge transfer designed for problematic SMEs has to meet the specific requirements of high transfer frequency and short time slots while maintaining a high quality. Continuous knowledge management systems are not available and knowledge transfer activities are usually initiated on demand. Therefore, the transfer method must be easy to use by the employees involved and supported by a moderator (figure 14.2, right). Employees exchanging knowledge should concentrate on the transfer of content. Instead of the well-known tree, structuring methods with limited capacity to model dependency networks, such as MDM methods, are used.

The knowledge transfer process is executed systematically. First, the knowledge domains have to be defined according to the specific use. Second, the expert (mentor) is interviewed and the knowledge receptor (mentee) is given the acquired list of knowledge components. All knowledge components and dependencies are visualized and discussed. Finally, the knowledge network (acquired from the expert) and the status of familiarity with the knowledge components (acquired from the receptor) are analysed using methods from matrix and graph theory. Based on the analysis, measures for knowledge transfer are agreed upon.

The relevant domains are usually tasks, competences, methods, and networks. A generic version of the basic domains and their relationships is shown in figure 14.3.



	Tasks	Compe-tences	Networks	Methods
Tasks	require	require	require	
Compe-tences	useful for	require		
Networks	support	generate		
Methods	required for	generate		

Fig. 14.3 System graph and Multiple-Domain Matrix (MDM)

Identifying networks of knowledge subsets from different domains has improved the quality of knowledge transfer by concentrating on specific parts of the expert's knowledge.

14.5 Design to Cost

Target Costing or Design to Cost in the field of mechatronic products is still problematic. Braun (Braun and Lindemann 2009) analysed the influence of dependencies within mechatronic products on the resulting costs in light of material and known costs in production processes.

It is possible to identify typical cost drivers. Complicated mechanical components, drives, sensors, special power electronics and components of special disciplines (e.g. optical systems) are often bought as complete assemblies. The system components are typically strongly interlinked in the physical component structure.

Strongly interlinked system components (i.e. components with many interfaces) of the physical and functional component structure generally have clearly higher costs than the other components in the structure (figure 14.4). They are easy to locate in the structures, as they tend to be in the centre of strength-based graphs.

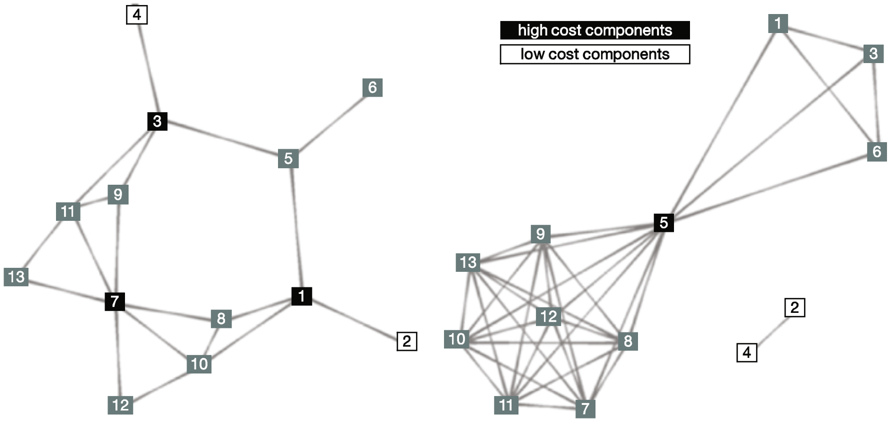
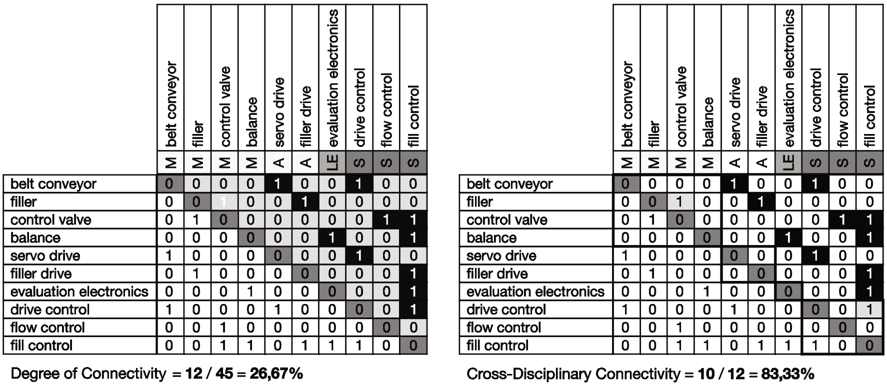


Fig. 14.4 Identification of high and low cost components in the physical (left) and functional (right) component structure

Exceptions arise if the “central node” of the physical structure is also an isolated node (and/or part of an isolated cluster) of the functional structure. This is also valid for the special form of an articulation node. The most upscale components of a system tend to be members of numerous complete clusters in the physical and functional component structure.

A “leaf-element” of the physical component structure is often an isolated node (or part of an isolated cluster) of the functional component structure and, in this case, comparatively low-priced. Leaf-elements of the physical component structure are usually interfaces to other assemblies, control units, covers or casings of the overall system.

Further statements specific to the disciplines involved have been derived. The category of ‘system spanning items’ mainly comprises statements related to costs of activities such as integration and testing.



	belt conveyor	filler	control valve	balance	servo drive	filler drive	evaluation electronics	drive control	flow control	fill control
	M	M	M	M	A	A	LE	S	S	S
belt conveyor	0	0	0	0	1	0	0	1	0	0
filler	0	0	1	0	0	1	0	0	0	0
control valve	0	1	0	0	0	0	0	0	1	1
balance	0	0	0	0	0	0	1	0	0	1
servo drive	1	0	0	0	0	0	0	1	0	0
filler drive	0	1	0	0	0	0	0	0	0	1
evaluation electronics	0	0	0	1	0	0	0	0	0	1
drive control	1	0	0	0	1	0	0	0	0	1
flow control	0	0	1	0	0	0	0	0	0	0
fill control	0	0	1	1	0	1	1	1	0	0

Degree of Connectivity = **12 / 45 = 26,67%**

	belt conveyor	filler	control valve	balance	servo drive	filler drive	evaluation electronics	drive control	flow control	fill control
	M	M	M	M	A	A	LE	S	S	S
belt conveyor	0	0	0	0	1	0	0	1	0	0
filler	0	0	1	0	0	1	0	0	0	0
control valve	0	1	0	0	0	0	0	0	1	1
balance	0	0	0	0	0	0	1	0	0	1
servo drive	1	0	0	0	0	0	0	1	0	0
filler drive	0	1	0	0	0	0	0	0	0	1
evaluation electronics	0	0	0	1	0	0	0	0	0	1
drive control	1	0	0	0	1	0	0	0	0	1
flow control	0	0	1	0	0	0	0	0	0	0
fill control	0	0	1	1	0	1	1	1	0	0

Cross-Disciplinary Connectivity = **10 / 12 = 83,33%**

Fig. 14.5 Comparison of measures: degree of connectivity (left) and cross-disciplinary connectivity (right)

For example, a higher degree of connectivity of the physical component structure may lead to comparatively higher costs for integration and testing. The degree of connectivity represents the ratio of existing edges to the quantity of all possible edges in a structure.

The degree of cross-disciplinary connectivity was introduced to measure the interdisciplinary connectivity of a system (figure 14.5). It appeared that cross-disciplinary connectivity is higher the more disciplines are involved in a system and that an increase results in higher internal system appraisal costs.

It is possible to increase the quality of cost estimation in early phases of the development of mechatronic products by using information gathered on the characteristics of the system's dependencies.

14.6 Process Planning

A plumbing installation process in the patient rooms of a large hospital had to be fulfilled as part of developing complex systems. The following section is based on a publication addressing the link to Lean Development (Furtmeier et al 2010).

A conceptual plumbing installation plan, based on expert knowledge and experience from past projects, had already been developed. The main purpose of the MDM application was to develop a plan for the most efficient delivery of plumbing services in the hospital. In the first step, the process development team laid out the installation tasks for the plumbing system in a cross-functional process map.

However, the cross-functional process map does not present any dependencies within the tasks. Hence, the flow of material is not illustrated in the process representation, and so the existence of more than one material flow and the dependencies between flows have not been recognized.

The cross-functional process map served as a starting point for the acquisition of information required to fill the two native DMMs that connect inventories and tasks. Input and output inventories were allocated to the tasks. With the information on hand, the DSM containing the network of tasks can be calculated from information stored in the two DMMs. The resulting DSM was presented graphically to aid further analysis. Several structural characteristics were identified that can help to improve the state of the map. Figure 14.6 shows the network of tasks deduced and pinpoints structural characteristics.

The structure deduced shows a highly interconnected subset and three sequential (bridge edges) paths connecting the subset with the end and start nodes. Articulation nodes connect these paths to the subset in the middle. The sequential paths can be seen as separate processes delivering to or receiving from the subset. They are connected by articulation nodes, which form bottlenecks, and therefore can define the processes' takt time. Furthermore, there are two feedback loops in the structure. In this case, these loops provide the opportunity for KANBAN to supply the materials. The left feedback loop pulls material out of the two paths. In addition, the structure shows similarity.

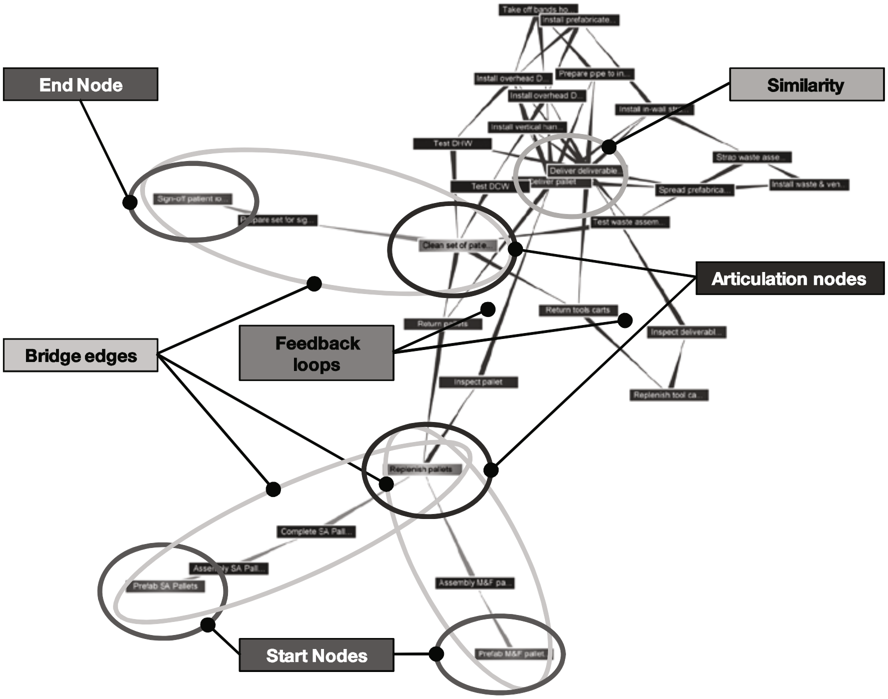


Fig. 14.6 Deduced network

This similarity highlights two tasks that can be integrated into one. As the tasks are both part of the feedback loop, it might be possible to integrate the feedback loops. Moreover, the structure has a hierarchy, beginning at the articulation node and connecting the end node with the subset in the middle. The hierarchy illuminates the material flows, converging in an articulation node. As illustrated in figure 14.7, three separate material flows can be identified.

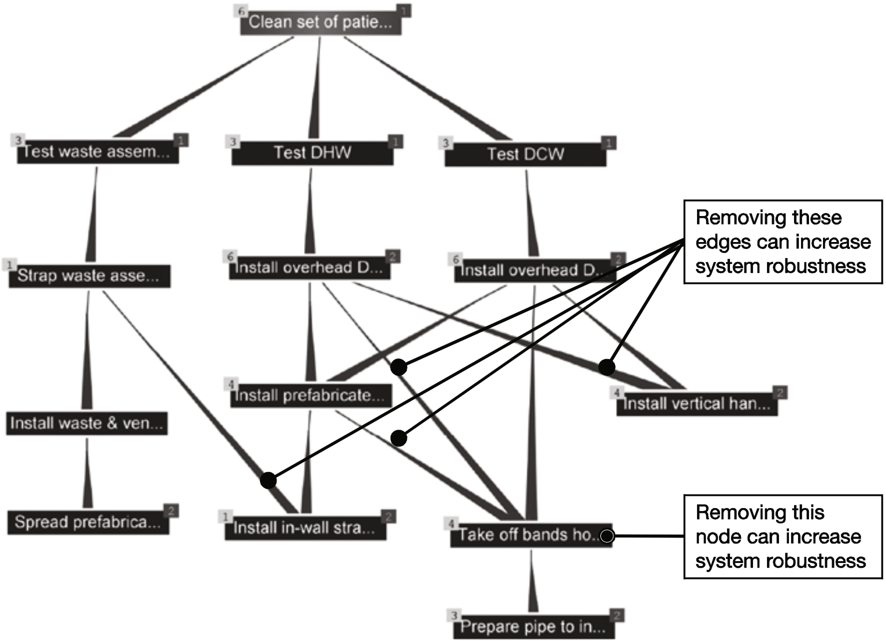


Fig. 14.7 Hierarchy showing three materials flows

By removing the edges between these three flows, the installation process' robustness and flexibility can be increased since the three flows no longer depend on each other. Removing edges or nodes can be done by rearranging steps or by finding different solutions for task completion. In this case, edges can be included in the prefabrication tasks.

14.7 Conclusion and Outlook

Understanding the characteristics of structures and their optimization possibilities creates many possible applications. These are improvement of the FMEA method (Maurer and Kesper 2011); change management (Lindemann et al. 2009); system architecture (Gorbea et al. 2010); safety and security (Maurer et al. 2009b), etc. The range of possibilities discovered in recent research on Systems Engineering should be checked, and useful methods and tools transferred to research and practice in engineering design.

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Chapter 15
The Autogenetic Design Theory
Product Development as an Analogy to Biological Evolution

S. Vajna[1], K. Kittel[1], T. Bercsey[2]

15.1 Introduction

Product development plays the key role in defining all product characteristics and benefits. There is a need for appropriate supporting methods that are able to serve and to satisfy multi-criteria and multilayer requirements. Today, these requirements go beyond function fulfilment; so additional requirements need to be taken into account. According to the Magdeburg approach of Integrated Product Development, these requirements can result from different characteristics, e.g. desired shapes, reliability and security, ergonomics, price-performance-ratio, manufacturability, serviceability, legal situations, sustainability, and other sources. They are all of equivalent importance and influence (Burchardt 2000) (Vajna and von Specht 2006).

The process of developing new products or adapting existing ones is highly dynamic due to the different types of changes that can occur during the development process. In most cases the changes are caused by modifications in the requirements. Other changes result from modified boundary conditions, changing resources or emerging technologies etc. In order to be applicable, a product development method should be able to react on any type of changes always in adequate ways and time frames.

Due to hard competition there is a need of a steady increase of the performance of the product. This means among others, that a product developer has to use the full capability of the solution space bounded by requirements and boundary conditions and to make use of flexible and powerful development methods, procedures, and tools. Most important of these is a product development method, which sup-

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ports the product developer in finding the best suitable solutions for a given task at any time, whereby there shouldn't be any limitation that would inhibit the finding of completely new kinds of solutions.

15.2 Basic Principles of the Autogenetic Design Theory

The Autogenetic Design Theory (ADT)[3] applies analogies between biological evolution and product development (Bercsey and Vajna 1994) by transferring the methods of biological evolution (and their advantageous characteristics) to the field of product development. Such characteristics are for example the ability to react appropriately on changing environments (requirements and boundary conditions), so that new individuals are in general better adapted to the actual environment as their ancestors. The ADT is not another variety of Bionics (where *results* of an evolution, e.g. the structure of trees, are transferred to technical artefacts). Rather, the ADT transfers *procedures* from biological evolution to accomplish both a description and broad support of product development with its processes, requirements, boundary conditions, and objects (including their properties).

The main thesis of the ADT is that the procedures, methods, and processes of developing and adapting products can be described and designed as analogies to the procedures, methods, and processes of biological evolution to create or to adapt individuals. Main characteristics of biological evolution (with the underlying principle of trial and error) are continuous development and permanent adaptation of individuals to dynamically changing targets, which in general have to be accomplished in each case at the lowest level of energy content and with the minimal use of resources, i.e. the evolution process runs optimised in terms of energy consumption and resource employment. The targets can change over time because of (unpredictable) changing requirements, resources, conditions, boundaries, and constraints, and they can contradict each other at any time.

The result of a biological evolution is always a set of unique solutions having the same value but not being of similar type. Consequentially, the result of the ADT is for the very most part[4] a set of equivalent, but not similar unique solutions that fulfil the *actual state* of requirements and conditions best.

Furthermore, biological evolution doesn't have prejudices. This means that new individuals (described by their chromosomes) will not be discarded because they are different. Each individual has to prove himself in his natural environment. If it turns out that an individual with a new chromosome set is superior to already ex-

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[3] During the ongoing research, the scope of the ADT has increasingly expanded from supporting the design process to supporting the whole product development process, i.e. is in change from "Design Theory" to "Development Theory".

[4] Theoretically it is possible that among the solution set there is one solution that dominates all other.

isting individuals, then this individual gets a better chance for reproducing. By transferring this behaviour of impartiality to product development, new concepts would not be discarded because they were totally different than former concepts but only if their properties were proven not to be superior.

This suggests that both evolution and product development can be described as a continuous but not straightforward improvement process or as a kind of multicriteria and continuous *optimisation* (Bercsey and Vajna 1994) (Wegner 1999).

One may argue that a weakness of the ADT is the processing (creation, evaluation) of a high number of individuals for reaching a certain product progress due to the evolutionary based approach. Compared to other methods, the number of solutions, which need to be evaluated, is in fact much higher. But one has to keep in mind that, by exploring this high number of possible solutions (individuals) within a solution area, the chance of finding the really best set of solutions to a given set of requirements, conditions, boundaries, and constraints is much higher than with traditional approaches that continuously delimit the solution area and thus result only in a single "next best" solution (Clement 2005).

The analysis of product development from an evolutionary perspective leads to the following insights (Vajna et al. 2005):

- In every phase of the product development process, various alternatives are developed and compared. These alternatives are in competition with each other, because only the best were selected for further processing.
- The processes of searching, evaluating, selecting, and combining are also typical approaches of biological evolution.
- Regardless of the phase of product development or of the complexity level of the emerging product, always a similar pattern of activities is used to modify existing or to generate new solutions, which is comparable with the TOTE-Scheme (Miller et al. 1991) (Ehrlenspiel 2007). Self-similarity can be found at all levels of complexity of product development as well as in all stages of the emerging product (Wegner 1999).
- According to chaos theory small changes or disruptions in the system can cause unpredictable system behaviour (Briggs and Peat 1990). The fact that the result of the development of a product usually can't be predicted definitely because of the influence of the creativity of the product developer leads to the assumption that the product development process also contains elements of a chaotic system or at least shows a chaotic behaviour in some aspects.

At the present state, three major components of the ADT have been researched. First, a process model describing how the ADT works and what the steps are, which the product developer has to perform. Secondly, the solution space model, which shows how the space, in which product development takes place, is structured. Thirdly, the underlying product model holds the description of how product information is structured and used.

15.3 The ADT Process Model

There are numerous ideas and concepts aiming on describing the complex and often chaotic process of developing. Caused by the complexity of most products, the focus within the development process is mostly not on the complete product, but rather on a specific part of the product. This means that each development step is focused on improving or modifying only one specific product property or a specific set of properties by varying certain design parameters. These steps should be followed by an intermediate step to ensure the product consistency.

The ADT process model currently under research aims on providing a holistic development process model that is also able to describe the processes of partial improvements/modifications, which normally do not follow a predefined pattern. The ADT process model describes the development process on two levels.

Level one provides an overall look on product development within the ADT. It starts with the definition and description of the target function[5] and the solution space (see the next chapter) based on requirements, starting conditions, boundary conditions, conditions of the environment of the solution space, and (internal and external) constraints. Within the solution space, possible solution patterns are searched, combined, and optimised in a random order. To evaluate the actual state of development, the particular fitness[6] is determined. Because requirements, processes, and both internal and external influence factors are all dynamic due to unforeseeable changes, it is clear that it is only possible to describe (rather small) process patterns, which can be used randomly, instead of specifying a sequence of steps or any predefined "way" the designer has to follow.

To nevertheless support the process of partial improvements or modifications (and allow the designer to address only a limited set of properties) without loosing both consistency and the overall picture, different views can be applied (see the product model chapter). These views act like filters that ensure that only a specific set of product properties are considered. Thus, the development process becomes a set of activities, each containing a product improvement or modification under a specific view.

Level two describes under a certain view the activities of improving or modifying a set of properties that are determined by design parameters. The ADT uses the steps *creation*, *evaluation* and *updating* to modify and to improve a product.

In analogy to biological evolution, the creation step consists of the four substeps selection – recombination – duplication – mutation.

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[5] The target function represents the synthesis of the optimisation goals derived from the requirements, which need to be fulfilled under certain conditions and in certain environments, even if these requirements contradict or exclude each other.

[6] The fitness is the representation of the actual level of requirement fulfilment.

- During *selection*, the parent solutions for the next generation were ascertained. In most cases, these will be the most advanced[7] parents. But also less developed have a minor chance of being selected. Especially in the early product development process selecting less developed solutions can help to explore the solution space better.
- Following selection is *recombination*. This is the usual way to create new solutions where the design parameters of two already existing solutions were combined to create (in most cases) a more evolved solution. In biological evolution the design parameters are selected randomly. In the ADT, the designer can influence the process of recombination (e.g. by experience) in order to speed up.
- An alternative is *duplication*, which results in the creation of a duplicate (clone). Creating clones is recommended if solutions with superior properties exist, which should be inherited to the next generation, to avoid that the quality of a solution gets lost during recombination with a less developed solution.
- The last sub-step is *mutation*. Mutation is used to randomly change a solution created by recombination. Just like in biological evolution, mutation is necessary to ensure dynamics in the evolution process. Mutation offers the chance to create a completely new kind of solution. But is has to be mentioned that the chance for such an event is rather small.

The creation step is followed by the evaluation step. In this step each new solution is evaluated to determine the fulfilment of the optimisation goals described in the target function. Based on this information the actual fitness is calculated. The method to determine the goal criteria depends on the goal criteria themselves. Common methods are e.g. analytic methods, Finite Element Methods (FEM), Computational Fluid Dynamics (CFD), and ergonomic studies. The calculation of a fitness value for each solution is necessary to compare the different solutions. The challenge here is to adequately represent all goal criteria in just a single value. To resolve this problem, different methods such as weighted goal functions or Pareto based approaches can be applied.

The last step is updating. An update of both solution space and target criteria is necessary to take dynamic requirements into account. Often requirements change within the development process. Such a change influences the solution space (with the result that a specific solution is not allowed any further) as well as the target criteria (with the result that a specific target criterion gets less important or that another criterion should have a bigger influence on the fitness).

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[7] "most advanced" doesn't mean the absolute value, but always a relation to the actual state of fulfillment of the target function.

15.4 The ADT Prohibition Space

In general, the term "solution space” is understood to be a set of all feasible solution elements, which can be used within the development. This includes all elements that a product developer may use for the evolution of a solution or several solutions, on the basis of requirements, inner and outer conditions, ecological/environmental conditions and others. This definition of a solution space can be compared with the mathematical term “domain”.

Every product development method has a solution space, which usually is spanned by the requirements and limited by both starting and boundary conditions. The inner structure is influenced by constraints. Some solution spaces, e.g. TRIZ (Altshuller 2003) and Gene Engineering (Chen and Feng 2003), use a solution space with a particularly structured dataset. This dataset contains the solution elements for the emerging solutions. It is common to all such solution spaces that the product developer is offered only a limited amount of possible solution elements. However, the more limited the quantity and possible configurations and combinations are, the lower is the achievable solution diversity and quality.

Thus, to improve both solution diversity and quality, it is necessary to not artificially limit the quantity of solution elements, but rather to include permissible elements for all concrete tasks. Thus follows, however, the task of holding on to all permissible elements in the solution space description. As the diversity of existing solution elements (materials, manufacturing methods, operating principles, etc) is immense, a complete solution space description at a reasonable cost is in most cases impossible[8]. Since the optimal configuration and combination of solutions elements are not available under these circumstances, the maximal possible solution quality can't be achieved.

In order not to limit the product developer and to permit the maximal possible number of allowable solution elements, the definition of the solution space within ADT is inverted. The only limitations of such an inverted solution space are the laws of natural science, i.e. the space is virtually infinite. The inverted solution space contains prohibited areas (taboo zones). Taboo zones are formed by those solution elements of which the use for possible solutions is explicitly forbidden. This inverted solution space is referred to in the following as *Prohibition Space*.

Another advantage of the Prohibition Space is evident in the early phases of the development process. Due to the lack of knowledge about the relationships between requirements and solution elements, it isn't often possible to determine the forbidden criteria, based on the forbidden requirements. The Prohibition Space therefore contains too few taboo zones at the beginning of the product development process. At this time, the product developer is able to use product criteria, for example, that should actually be forbidden. If, for example, impermissible solution elements are used, it will be noticed upon evaluation that the resulting solu-

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[8] Potential exceptions are tasks with very specific requirements, which leave only a very small range for possible solutions.

tion possesses impermissible product criteria. This newly obtained information can be used to refine the Prohibition Space.

A traditional solution space would in the same case be incomplete as well (due to the lack of knowledge about the coherences). Here, however, "incomplete" means that permissible elements are missing, thereby restricting the product developer's solution possibilities. Since a traditional solution space consists by definition of only permissible solution elements, only solutions with permissible criteria will be generated (exceptions could be certain combinations of permissible elements). So, an incomplete solution space can not be noticed at all even if the provided solution elements by far do not represent all possible solution elements.

The definition of the Prohibition Space is based on the requirements and the various starting and boundary conditions, constraints, and the environment, which can arise from different sources.

Through the inversion, requirements and conditions turn into appropriate bans that can be formulated and the solution elements that are forbidden can be derived. It is important to pay attention that n:m associations are involved between requirements, boundary conditions, and solution elements. For the sake of an overview, it is useful to group forbidden solution elements into taboo zones, e.g. possible categories are operating principles, materials, manufacturing methods, geometric parameters, standard parts, tolerances, surface finishes, etc.

In the early phases an assignment is not always possible, as for example, the relationships between product criteria and the originating design parameters are not always evident. Unassignable requirements are therefore temporarily not given further consideration. The set of forbidden elements can be further detailed later in the product development process, after knowledge about the influence of design parameters and product criteria is collected. If certain solution elements prove to not fulfil a requirement, this particular element will be added to the taboo zones.

The Prohibition Space dynamically changes whenever an external event (for example a requirement modification, a change of a condition, etc.) occurs during the evolution, because, as a result of this external event, changed possibilities for the evolution can arise or existing ones have to be omitted. To reflect these, taboo zones within the Prohibition Space have to be re-designed, which may result in changing taboo zones, in omitting existing, or in adding new zones (figure 15.1).

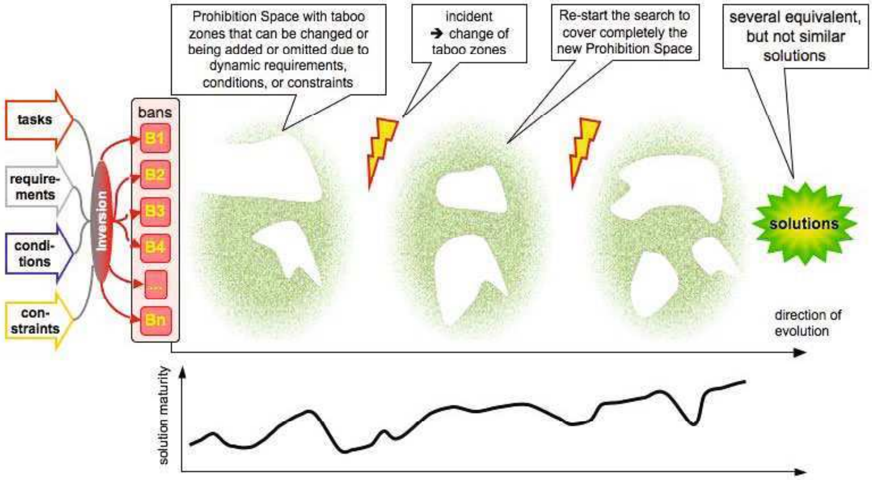

Fig. 15.1 Inversion of requirements and changes of the Prohibition Space due to external events

15.5 The ADT Product Model

The aim of a product model is to provide a framework to capture in a structured way all product data, which are necessary to describe the product and its life cycle. This framework shall be stable for the whole development process, so that the data can be complemented step by step. In "traditional" product development, different data structures arise along the sequential phases of the product development process. Skipping a phase is not possible.

The ADT product model is based at present on the extended feature model of the FEMEX, because this model provides a unified structure, which stores all product data and information from the whole life cycle (Ovtcharova et al. 1997).

The ADT product model is a modified model of the extended feature model, in which a product is described by a certain number of design parameters (represented by the different coloured boxes in figure 15.2). Each design parameter describes a fraction of the product. It has to be mentioned that a design parameter is not equivalent to a geometric parameter. The totality of all design parameters clearly defines all product properties, but there isn't always a 1:1 correlation. The aim of the product model is to structure the design parameters in order to improve clarity and usability. This is achieved by defining different views on a product (as mentioned in the chapter on the ADT process model), as shown in figure 15.2.

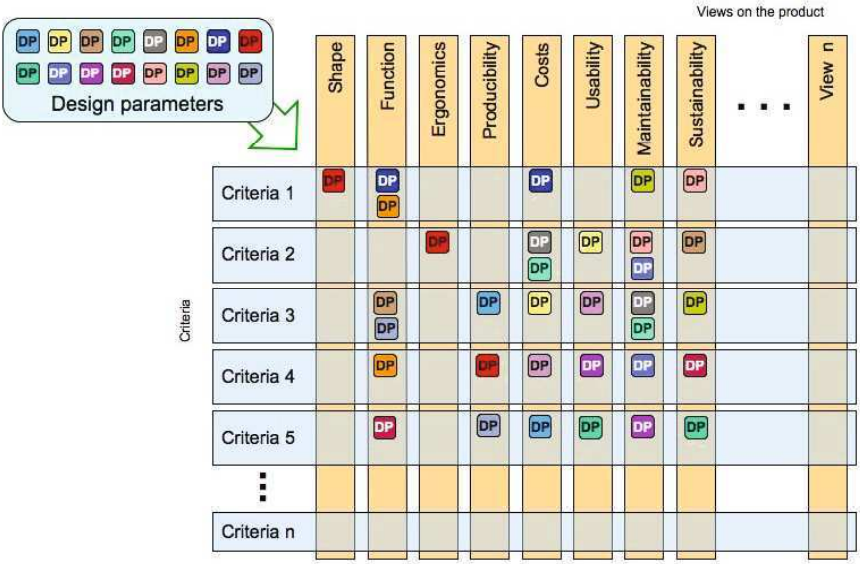

Fig. 15.2 The ADT product model

Each design parameter can appear in a single view or in multiple views. The assignment of the design parameters is displayed on the horizontal axis, while the vertical axis displays the product criteria. This assignment shows, which design parameter(s) is (are) needed to fulfil a certain product property. In order to classify the design parameters in the matrix, a meta information (tag) can be assigned to each of them. Using tags, each design parameter can be equipped with additional information. This additional information can be the design parameter type or the product property influenced by the design parameter. The system of using tags can be extended to provide the design parameters with a lot of useful information.

An advantage of this form of representation is that the influence of design parameters can be quickly determined. It can easily be checked, which design parameter influences which particular property. Product properties that depend only on a single design parameter can be determined at the very beginning of the development process without taking into account dependencies with other product properties (as long as the design parameter is not influencing other properties). This dependence can be checked very simple by analyzing the tags of the design parameters.

The ADT product model allows the representation of design parameters in a way similar to the form of a biological chromosome. In this context a chromosome contains all design parameters that define a certain property.

The values of the included design parameters of the chromosome are variable along the development process. The design parameters of the considered chromosome can change triggered by different events. Possible types of events are:

1. Optimisation of a design parameter. This is the most common case. The product developer adjusts a design parameter to achieve an improvement of a product property.
2. Changes due to dependencies. When a design parameter changes, it is possible that a thereof dependent design parameter must be adjusted, e.g. if a design parameter dictates a material and another design parameter dictates the wall thickness. In this constellation it can occur that the design parameter wall thickness has to change when the design parameter material changes, because not all former values were permitted any longer.
3. External event. By a change in the requirements new or adjusted taboo zones arise. This new circumstance can create the need that design parameters need to be adjusted, because certain values are not permitted any longer.

15.6 Conclusion and Outlook

This description of the different components of the ADT shows the concepts that have been developed so far.

The process model represents a rough description of our idea of a product development process as an analogy to biological evolution. This process model will be refined as the other components reach a more detailed state.

The research on designing the solution space for the ADT has shown that the approach of describing a solution space in a form of a "closed volume", i.e. by a complete and consistent description of every boundary component, can't always be realised, thus leading to solutions that stay below their theoretical solution quality. The approach of the Prohibition Space with taboo zones leads to much more flexible and lucrative results, as first tests have already shown.

The ADT product model offers a way to describe a product detached from its actual physical structure. This allows the application of the product model even in the early phases of the development process.

Future research work on the ADT will deal with incorporating and supporting requirements and conditions that result from the development of mechatronical products. Therefore, the existing approaches, methods, and models within ADT will be toughened up in order to handle these kind of multidisciplinary products and the significantly increased amount of data resulting from this multidisciplinarity. Thereby it has to be ensured that the ADT remains generally applicable.

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Chapter 16
Towards a Designer-Centred Methodology: Descriptive Considerations and Prescriptive Reflections

P. Badke-Schaub[1], J. Daalhuizen[1] and N. Roozenburg[1]

Abstract Design methodology aims to provide structure that supports designers dealing with complex and complicated problems in varying projects, contexts and environments. For decades, the technique for transferring methods into practice has been discussed, mainly in reference to the limited use of methods in practice.

This paper addresses three issues: past, present, and future. 'What is methodology good for?' is asked in reference to the past and provides a brief overview of arguments from recent decades that question the benefits of design methodology. The second part elaborates on the claim that designers should be the source of information about their use of design methods. To support the plea for a designer-centred methodology, results are presented of an interview study that aimed to find out what kind of situations the users of design methods - the designers - experience as non-routine situations and how they cope with these kinds of situations. It is assumed that this information helps to determine when designers need what kind of support. Finally, the third section discusses the extent to which the new design thinking movement as a business strategy will influence the development of design methodology in the future, and closes with a summary of the implications of future trends for design methodology. The emphasis throughout is a plea for substantial methodological support in an individually personalised and situation-oriented manner to meet the demands of the user, and thus increase design performance.

> The most innovative designers consciously reject the standard option box and cultivate an appetite for thinking wrong.
> (Marty Neumeier)

16.1 The PAST: What is Design Methodology Good For?

Design methods have the potential to improve designers' performance by providing structure to their actions and thoughts. Designing is a highly challenging task

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and, due to globalisation, new technologies and societal changes, the problems designers encounter are becoming more complex, and companies face a greater risk of failure. Thus, structural procedures that support people in coping with these uncertainties should be most welcome.

16.1.1 The Two Faces of Design Methodology

Is experience a critical factor in creative design processes? What kind of strategy can prevent fixation during idea generation? Which selection strategy is most appropriate when there is time-pressure?

These questions are examples of only a few aspects of knowledge necessary to understand the design process and the designers' behaviour. This kind of knowledge delivers the foundation for hypotheses on how designers should work efficiently and effectively. The hypotheses are the source for developing prescriptive methods that should support the designer.

If we assume that designing is not an innate or purely artistic ability but is a procedure that can be taught and learned, knowledge is needed about the thoughts and actions of designers throughout the process of designing in various contexts to create methods that are aligned with their needs. Accordingly, there are two aspects to design methodology: descriptive and prescriptive (Cross 1989).

The first prescriptive methodologies were developed in the area of mechanical engineering (Hansen 1956, Kesselring 1942) and, like the more general design methodology in design research, were developed based on abstraction and generalisation of observations and experienced design activities in industry (Rodenacker 1970, VDI Guideline 2222 1973, Hubka 1973, Pahl and Beitz 1977). Prescriptive approaches were based on descriptive knowledge abstracted from people and focusing on the process.

The gap between design prescription in design methodology and how it is perceived and experienced by practitioners was a major concern from the start. Within the design methods movement, two of its founding fathers, Alexander (Alexander 1971) and Jones (Jones 1977), criticised the first generation of design methods early on. Jones stated, for example: "I dislike the machine language, the behaviourism, the continual attempt to fix the whole of life into a logical framework".

Much earlier, Wögerbauer (Wögerbauer 1943) identified the need for psychological aspects to be included in the creation of a field of engineering design (Konstruktionslehre) that is close to practice. However, scientific interdisciplinary cooperation between designers and psychologists only began in Germany in 1985. A team composed of cognitive psychologists from the University Bamberg, mechanical engineers from TU Munich and engineers from TU Darmstadt (Pahl et al. 1999) aimed to investigate design activity more faithfully by analysing the characteristics of the designer, the task and/or the team. Questions were asked, such as:

Design methodology should support the designer, but who is “the designer”? How do designers arrive at a successful solution? What kind of successful processes of thinking and reasoning can be described and how can they be supported? Which mistakes occur and how can the proposed procedures and methods help to avoid these mistakes and improve the design process?

16.1.2 Deficits of Design Methodology

Many authors throughout the history of design methodology have pointed to the problematic transfer and application of methods into practice (for example, Birkhofer et al. 2005, Jaensch 2007); various explanations have been given for the disappointingly low level of acceptance of methods in practice. There are three main categories of deficits in design methodology (figure 16.1):

1. the questionable performance of methods
2. the ways that methods are presented and formulated
3. process-related problems during the application of methods.

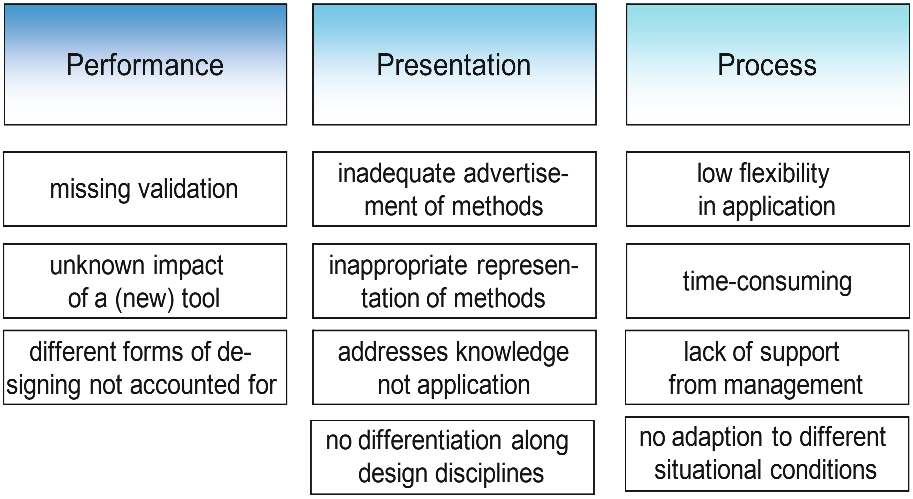


Fig. 16.1 Deficits of design methods referred to in literature

The first issue relates to the performance of methods and addresses the question of whether it is proven that design methods really lead to superior design performance. Even when methods are applied, the design performance can still be low because of poor use of methods or the quality of the method itself. Low performance can be caused by a mismatch between characteristics of the chosen method and the task or problem at hand, or due to incorrect timing in the process.

Birkhofer (Birkhofer 1993) presents an example of a methodologically based design process in a small engineering office: the development of a plastic bag dispenser for supermarkets. A group of highly experienced designers engaged in the development of this new product, with increasingly challenging demands during the process. The engineers developed several solutions and faced several drawbacks but finally reached a good solution by working in a methodological way. However, there were more time and investment costs compared to planning as a consequence of an escalation in commitment (Staw 1976). Five dispensers were produced and delivered to supermarkets. It was a product flop because there was no acceptance by the end user for several reasons, such as plastic bags being seen as environmentally unfriendly and many people not using bags in the supermarket because they put their goods in their shopping trolley then take them to their car. After a few weeks of placing the dispensers in the supermarkets, the numbers of sold bags was so much lower than expected that the dispensers were removed.

It is very difficult to prove the superiority of using methods. It is also very difficult to analyse the impact of introducing new methods. Another issue related to the performance of methods is the criticism that methods do not account for different forms of designing (Visser 2009).

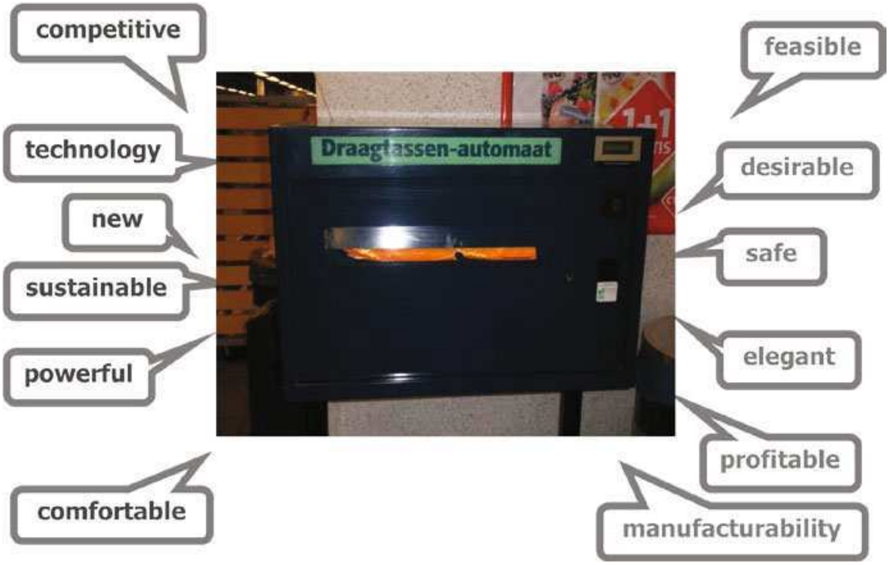


Fig. 16.2 Dutch example of a plastic bag dispenser

The second issue is the non-user-friendly representation of methods: engineering design methodology can portray the technical context of formulas and diagrams in an unappealing form. The same is true of the abstract language used to describe the procedures of methods, which seems to be inappropriate for use in practice. Practitioners focus on the problem at hand in a solution-focused way rather than on the process of design methods. Thus, methods are too complicated (Stetter and Lindemann 2004) and too theoretical, and are therefore hard to remember. Furthermore, the representation of methods is more about mediating knowledge and less the ability to apply them. Therefore, finding and selecting suitable methods is extremely complex and difficult for designers in practice (Cantamessa 1997, Araujo 2001, Birkhofer et al. 2002).

The third group of arguments relates to using design methodology during the design process. Based on an industry survey, Araujo (Araujo 2001) concluded that low acceptance of methods in practice is caused by a lack in organisations of interest and managers, resources for transferring and adopting tools, and promotion practices by non-commercial, disseminating organisations. Other authors point to a lack of commitment from top management, lack of necessary tool use skills in the organisation, and unrealistic expectations of the consequences of the use. The most frequently named obstacles are time consumption and inflexibility of methods (Jorden 1983, Rutz 1994). In becoming more aware of the influences of context, it is also argued that design methods should relate more to the specific situation or patterns of situations (Eder 2009, Badke-Schaub et al. 2005).

A lot of effort has been invested in finding out that designers do not usually work to the guidelines of design methodology. More important was the general recognition of the context of the designer, the social context of designing, as well as the environmental context. A broad range of case studies in industry observed the work of designers in their work environment and analysed the variables and their links that contribute to an increase of uncertainty in design practice and which need to be addressed (Badke-Schaub and Frankenberger 1999, Kleinsmann et al. 2005) in design methodology. It became clear that many influences set the tone of a situation and that the interwoven network determines whether the design process and output are successful.

> What man desires is not knowledge but certainty.
> (Bertrand Russell)

16.2 The Present: Do Designers Need Design Methodology?

If design methodology does not relate to the specific situation and person, it seems relevant to question whether designers need design methodology. The process the designer should follow may be explicitly prescribed by a particular method. However, the characteristics of the individual designer, such as experience, influence thought and actions and thus their choice of methods. Designers vary in knowledge, experience and skills; the social context varies in complexity, uncertainty, dynamics of communication and cooperation. This is also true for characteristics of the specific task and project context, such as the organisational environment, time constraints, financial constraints, and constraints associated with multiple projects that must be treated simultaneously. This then raises the question of what kind of problems would prompt a designer to request supporting methodology.

16.2.1 Uncertainty as a Consequence of Routine and Non-Routine Situations

Designers develop innovative products, services, and experiences. Innovation is the result of inventive processes that are new situations where solutions can only partly be derived that they are non-routine situations. Consequently, from a psychological point of view, designing is an activity that entails dealing with uncertainty.

People use varying strategies to deal with uncertainty; thinking is based on representations of reality that are created in order to understand, predict and explain the world. Reason (Reason 1990) distinguishes between two basic cognitive processes responsible for identification and selection processes: 'similarity matching' and 'frequency gambling', which he describes as 'computational primitives of the cognitive system'. The identification and selection of adequate actions are based on prior experience of a similar situation. Which 'piece of experience' is chosen for identification and action selection is based on the similarity between the given situation and the schemata stored in memory. If this similarity-check process does not lead to clear identification or an adequate action selection, then prior knowledge that has often been addressed successfully in a related situation or context is elicited. Thus, thinking is primarily steered by (adequate or inadequate) existing schemata, which is very effective and efficient in routine situations because a quick response is possible.

In the case of non-routine situations where there are no suitable schemata available, new schemata need to be generated, which gives rise to uncertainty. Individuals have varying levels of tolerance of uncertainty and ambiguity (Frenkel-Brunswik 1948), which affects thoughts and actions on several levels of behaviour: from past situations and where the outcome can rarely be predicted during the design process. Thus, next to novelty, complexity, and unpredictability, a fundamental ingredient in designing is uncertainty. Uncertainty, as a psychological state, emerges when information is missing, unclear or contradictory, when situations are too complex to oversee and the interdependencies are incomprehensible. The common occurrence of ill-defined design problems implies Cognitive reactions, such as reducing complexity by changing an ambiguous situation into an unambiguous one, e.g. reframing situations into black or white what decreases the cognitive load (Sweller 1988).

1. Emotional reactions relate to expressions of dislike, anger and anxiety, which again affect thought processes, e.g. fear of failure or belittling of serious problems or observed consequences.

2. Behavioural reactions refer to responses such as rejection or avoidance of uncertainty, e.g. blaming others for causing uncertainty.

Uncertainty is a state of mind that people can only deal with for short periods; cognitive mechanisms usually work continuously to reduce uncertainty. There is an obvious clash of interests in the cognitive system; the complexity of design problems enforces economical tendencies, which means economical use of the limited resource ‘conscious thinking’. Unfamiliarity with the new situation causes the need to seek or develop new schemata, which increases cognitive complexity. This conflict between an increase in uncertainty and the need for reducing uncertainty may prevent the most appropriate solution being sought, in favour of the simplest results (simplicity principle (Chater 1999)). The cognitive system attempts to seek the simplest solutions to reduce uncertainty as much as possible. The risk in the context of complex problem solving is that the simplest solution is often not the best. Here, design methodology can support the designer in reducing cognitive effort, thus reducing uncertainty and avoiding inappropriate strategies.

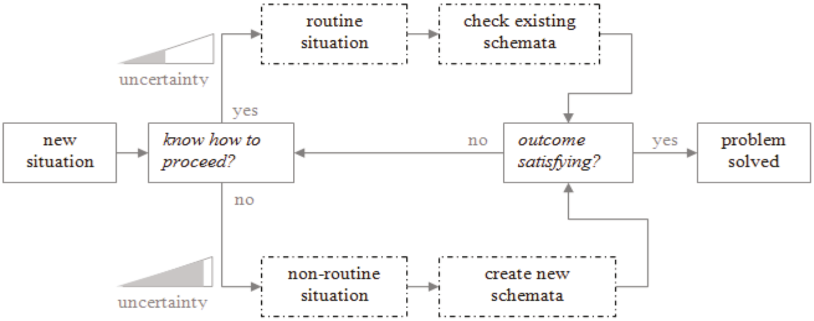


Fig. 16.3 Uncertainty in non-routine and routine situations

The process above is not necessarily accessible to conscious thought. Depending on the designers’ perception, the situation will automatically be compared to those stored in memory. These cases are a combination of a specific situation and one or more corresponding responses. The more experienced a designer is, the more often this will lead to intuitive responses. Design practitioners rely mainly on their knowledge of previous successful processes, which does not necessarily lead to successful innovation.

16.2.2 The Users’ View

There are several ways to develop methods. As outlined above, to arrive at valid prescriptive guidelines it is important to understand the interdependencies in the design process and the activities during the process. One way to arrive at this knowledge is by using the designer as the expert of their own design process. When does the designer want to be supported? Which situations do designers experience as non-design situations and how do they deal with these situations?

An Interview Study

16 design practitioners in six design companies in the USA and the Netherlands were interviewed. The data were collected through open-ended, semi-structured interviews (Daalhuizen et al. 2009). The interviews were designed to find out what kind of situations designers describe as non-routine and in which they felt 'inefficient or ineffective' or 'out of routine'. They were asked about the origin of the specific non-routine situation and how they dealt with these situations. Their answers included both procedures that they developed personally and the use of known design methods. The sample was heterogeneous in terms of experience level, expertise and work domain. The experience-level ranged from 1 to 30 years of work experience. The expertise domains ranged from new business development to developing manufacturing strategies and project management. The work domain ranged from product design to user research and mechanical engineering. The data were analysed according to the 'Framework' method (Ritchie and Spencer 1994).

Sources of Uncertainty

First, the perceived sources of uncertainty in non-routine situations were analysed. Each of the non-routine situations fell into one of the following categories:

1. uncertainty attributed to the *individual*
2. uncertainty attributed to the *social context* in which the designer was embedded
3. uncertainty attributed to the design *task*.

Although uncertainty will always be a part of designing, it is only of major influence when it increases to a level that overwhelms the designer and thus adversely affects their performance and prevents them from achieving their goals. This will either lead design practitioners to reflect on the situation and develop new responses or apply a known procedure despite the unfamiliarity of the situation.

Uncertainty attributed to the individual

The performance of designers is governed by their abilities and experience. Uncertainty attributed to the individual is caused by the absence of having the required knowledge, rules or skills to proceed in a way that is appropriate to the problem at hand. In these situations, uncertainty is associated with the person.

Uncertainty Attributed to the Social Context

When working with others, a designer needs to exchange information and arrive at commonly accepted decisions. Uncertainty attributed to working with others is caused by the absence of information exchange needed to proceed in a way that is appropriate to the problem at hand. In these situations, uncertainty is associated with the interaction between the designer and other team members. Issues like trust and shared understanding play a crucial role.

Uncertainty Attributed to the Task

'Uncertainty attributed to the task' is caused by task complexity and the necessity to proceed in a way that is appropriate to the problem at hand. In these situations, uncertainty is associated with the task itself.

Results

Analysis of the frequency of occurrence of non-routine situations reveals that designers encounter a variety of situations that can be categorised according to the three sources of uncertainty, as illustrated in the following figure. The data indicate that 46.3 % (n = 54) of the non-routine situations are attributable to the task, 46.3 % to the social context and only 7.4 % to the individual's abilities or behaviour.

Figure 4 shows that most task-attributed non-routine situations were caused by changes in the understanding of the problem during the process, such as a sudden change in the design brief or a new interpretation of the task, making it inappropriate to continue with the same course of action. The designer's representation of the task shifted, which then created a need to develop or introduce a new way of approaching the problem. In addition, many non-routine situations occurred because the designer was operating at a strategic level instead of an operational level. In these cases, issues needed to be analysed, and results articulated in a language appropriate to strategic decision making.

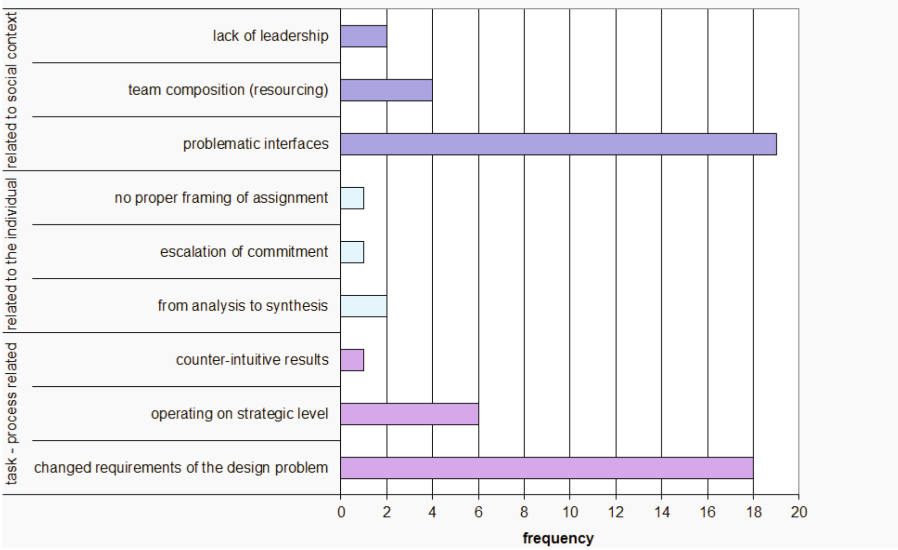


Fig. 16.4 Non-routine situations categorised according to the origin of the situation

Designers attributed significantly fewer non-routine situations to their own personal abilities and behaviour compared to the task or social context. Situations that related to the individual were problems with the transition from analysis to synthesis during the design process, escalation of commitment to a sub-optimal solution, or improper framing of the assignment.

Non-routine situations attributed to the social context were mostly related to interfacing with others. In these situations, the designer did not have a similar understanding of the issue at hand as other people, i.e. clients, users, colleagues etc. This may result in conflict between the designer and client or user, etc. or an inaccurate understanding of the design task within a design team.

In summary, most of the reported causes of non-routine situations were either the task or the social context. This is important because it implies that designers usually attribute the occurrence of a non-routine situation to something or someone outside themselves. The variety of non-routine situations is also broader than is usually addressed in the design methodology literature.

The second question related to the measures taken by designers when confronted with any kind of non-routine situation. This question is designed to reveal which methodological approaches are commonly used in practice and where further support might be needed. Again, the results were grouped into the same categories of the individual, others and task-process.

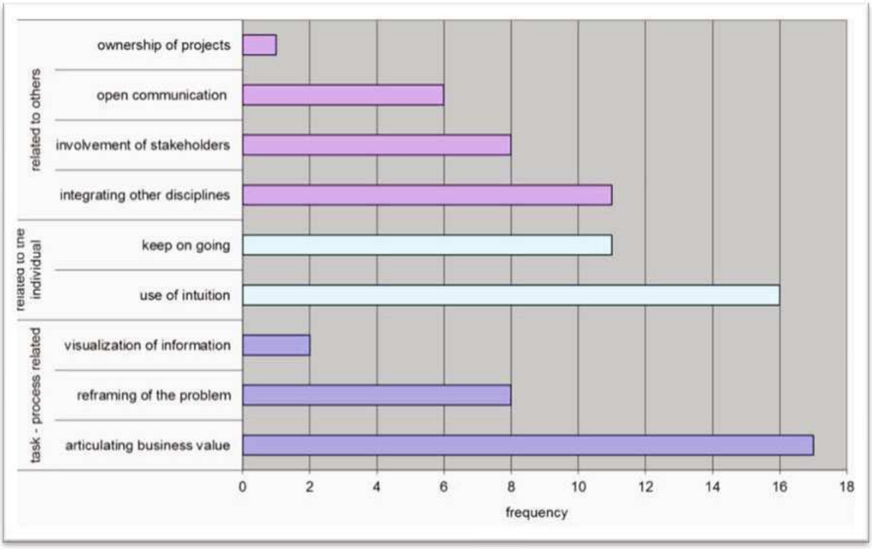


Fig. 16.5 The actions of designers in non-routine situations

Figure 16.5 illustrates the variety of strategies that designers use in dealing with non-routine situation. The most frequent strategies mentioned by designers are:

1. Involvement of people who are in the same boat: other disciplines, stakeholders, etc.: Many situations include working and communicating with multiple stakeholders who have different backgrounds and goals. This often causes communication problems due to the cognitive distance between the mental models of stakeholders being too large, meaning the design problem is understood in very different ways. In these cases, designers try to involve the stakeholders throughout the process to increase common understanding of both the problem and the design process and decrease the cognitive distance. When the cognitive distance reaches an optimal minimum, stakeholders can even contribute in a fruitful way to the innovative performance of the team.
2. Maintain motivation and rely on personal experience (intuition): Designers encounter many situations in which goals are ill-defined and the solution space is large. This combination can induce a strong feeling of uncertainty and cause the designer to hesitate or stall. When this happens, designers invoke a range of strategies, such as involving colleagues, building a physical model, or keeping a positive attitude, that keep them going in spite of the high level of uncertainty.
3. Articulating business value: Many of the non-routine situations occur when designers work at a strategic level. The client requires an understanding of the business value of the solution, even while it is being developed. These situations require designers to present their solutions in a business context. Design-

ers try to articulate the relationship between their understanding of the problem and the solution they have developed. In this way, they express the strategic value of the solutions they are developing.

Some design project teams lack a hierarchical structure. This might be beneficial in an open team climate but it can cause situations in which nobody takes responsibility for the project. In this case, designers can try to take ownership of a project and introduce a coherent structure.

If we compare these strategies that designers use, it becomes obvious that they do not have clear guidelines on when to use a procedure or how to choose the one that is most helpful. The non-routine situations mainly relate to cooperation and coordination questions and to sudden changes in the requirements of the design problem.

In order to develop a designer-centred methodology an *understanding of the needs for methodological support of the designer is essential.* Therefore, design methodology needs to consider the following:

1. The designer is always operating in a context: what is the problem the designer is dealing with in the social and organisational environments?
2. *When does the need for methodological support, occur, and why?*
3. Every designer has a different personality and so plan and execute the process differently: to what extent is the designer capable of working with uncertainty, and to what extent is the application of a method helpful, necessary or superfluous?
4. Methodology needs to provide an infrastructure that facilitates the use of methods, decreases the barriers and reduces time: *how should design methods be transferred into practice?*

> Method is much, technique is much, but inspiration is even more.
> (Benjamin Cardozo (1870-1938))

16.3 THE FUTURE: Design Methodology as A New Business Model

This final section discusses the current competitive advantage of the new design thinking approach. The chapter closes with some implications for the future of design methodology.

16.3.1 Design Thinking as 'Design Methodology-lite'?

Design methodology has been discussed rather critically and even opposed in its own discipline for decades. (Roozenburg and Eekels 1995). Methods are always under suspicion of violating creativity and innovation. This prevailing suspicion might have been the key to the success of a new 'movement' initiated by practitioners from business and management under the term 'design thinking'. This movement is an overarching holistic and interdisciplinary approach for innovative problem solving (for example, Brown 2008, Brown 2009; Martin 2009; Verganti 2009), mostly by providing a competitive edge due to innovativeness, for a product, system or service.

This new design thinking movement is partly a response to the criticism from management education and research in business schools, and partly a business strategy. Practitioners and academics claim that the education is too narrow and does not provide the skills needed in contemporary business, such as creativity.

In his book "Change by Design: How design thinking transforms organizations and inspires innovation", Tim Brown (CEO of the design consultancy IDEO) presents design thinking as being essential to meet the need for innovation and thus, cope with current and future global challenges. Brown (Brown 2009) describes design thinking as "an approach to innovation that is powerful, effective, and broadly accessible, that can be integrated into all aspects of business and society, and that individuals and teams can use to generate breakthrough ideas that are implemented and that therefore have an impact" (Brown 2009, p.3).

One of the most detailed definitions on design thinking was provided by Victor Lombardi, Vice President of Global Product, Fox Mobile Group, who referred to the following six aspects as the main characteristics of design thinking (http://noisebetweenstations.com/personal/weblogs/?page_id=1688):

- **Collaborative: working together with people with different** and complimentary experiences.
- **Abductive: reasoning and creating new options and solutions**
- **Experimental**: building prototypes and testing them according to hypotheses
- **Personal**: individual centred, focusing on the unique context of each problem and the people involved
- **Integrative**: a systems view of links between variables
- **Interpretive:** definition of the problem and evaluation of possible solutions.

Other authors claim design thinking is mainly a visionary strategy (Lockwood 2009; Martin 2009; Verganti 2009) and envision the designer's power to influence the world and thus have an impact on society. Brown (Brown 2009) describes the designer as a design thinker who is supposed to realise innovation.

"Design thinking is an approach that uses the designer's sensibility and methods for problem solving to meet people's needs in a technologically feasible and commercially viable way. In other words, design thinking is human-centred innovation.” (Brown 2009)

Compared to design methodology, the new design thinking approach offers less clear procedures, is fuzzier and does not give clear instructions on what to do and how to deal with different requirements in different ways. Unfortunately, there has been hardly any scientific research to investigate these assumptions. The traditional concept of design thinking has been established and widely accepted in the scientific community for three to four decades. It is mainly driven by empirical research and has produced detailed results about design thinking. The ‘new’ movement seems to ignore this approach by ambiguously redefining the core principles and ignoring results from ‘design thinking’ research (Badke-Schaub et al. 2010).

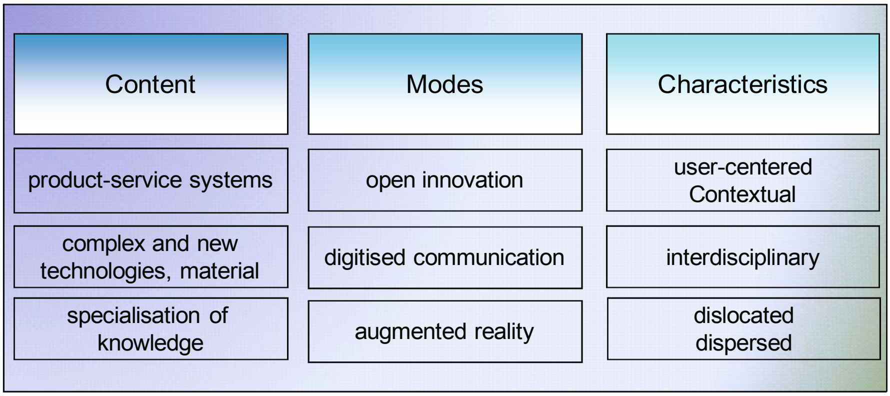
The current ‘new’ design thinking movement has been mainly a practice-based enumeration of aspects of the design process at low resolution, that stresses the relevance of activities, such as collaboration, exploring and integrating options, low-fidelity prototyping and interpretation.

The instructions are not deducted empirically or theoretically, as mentioned by Norman (Norman 2010) in his column “Design Thinking: A Useful Myth?”, calls the approach a myth that “is nonsense, but like all myths, it has a certain ring of plausibility although lacking any evidence.”

16.3.2 Implications for the Future of Design Methodology

Extrapolating the current situation into the future is difficult, especially as people have the tendency to forecast linear developments and conservatively extrapolate qualitative changes. Thus, only a few developments that indicate challenges for design methodology in the future will be mentioned here.

It is obvious that products are nowadays often connected to services and this development will continue. The possibilities, through new technologies, processes and materials, will continue to grow, along with knowledge specialisation.



Content	Modes	Characteristics
product-service systems	open innovation	user-centered Contextual
complex and new technologies, material	digitised communication	interdisciplinary
specialisation of knowledge	augmented reality	dislocated dispersed

Fig. 16.6 Content, modes and characteristics of designing in the future

The direct environment of the designer will change; a completely new way of designing is happening in open innovation projects. Communication modes are changing due to the geographically dispersal of project members. The heterogeneity of project teams will further increase and communication will become even more digitised due to the involvement of many parties in the design process and international cooperation. In this context, Augmented Reality will not be limited to gaming but will become more important and a steadily increasing part of daily life.

How can design methodology keep up with these developments? There is no answer to this question but there are some aspects that could be taken up by a methodology that aims to support the designer with the above-mentioned challenges of the future.

To understand the need for and use of methods by practitioners, the behaviour of designers in laboratory and field environments needs to be analysed. Field studies aid comprehension of the real world; laboratory research is needed to gain foundational knowledge on clearly defined questions. Empirical research should make use of existing theoretical knowledge, such as psychological theory, to understand how designers respond to the uncertainty of complex, difficult problems when under time pressure in a defined context.

If design methodology is to support designers appropriately, the designer must be able to choose an appropriate method in a particular situation, given a set of characteristics specific to the interaction between the designer and the situation. This integrative view aims to overcome the most important limitation of design methodology: the missing link to the ‘human’ characteristics of designing, neglecting the designer’s needs in the design situation of a specific task when seeking to solve the problem at hand. Because the basic principles of design methodology offer essential support for designers, this knowledge is built upon and needs to be integrated with the human aspect. By understanding designing as a complex problem-solving process steered by human cognitive and motivational systems in a complex environment, deeper insight into the way designers work is achieved. Ultimately, this may help to develop supportive methods and tools for the designer. Thus, future development needs to address the designer as a human and, in so doing, foster a designer-centred methodology.

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Chapter 17
A New Perspective on Product Engineering Overcoming Sequential Process Models

A. Albers[1], E. Sadowski and L. Marxen

Abstract In recent decades, the role of human individuals in product engineering was neglected as more and more effort was put into developing computer tools. A major factor in design that will never change is humans being at the centre of product engineering. Recent approaches of modelling product engineering processes as a sequence of activities neglect the complex interrelationships of activities carried out by parties participating in the process, as well as internal and external factors that influence the system of objectives, the operation system and the system of objects.

A framework is presented here that aims to overcome the difficulties in current process models. Management and engineering perspectives of a product engineering process are different but equally important. Sequential approaches do not successfully satisfy both. Product engineering can be described as the transformation of objectives into objects. To do this, the C&C²-Approach is needed as it permits the description of form and function simultaneously. The importance of validation in product engineering is described and the result of these investigations presented: The Integrated Product Engineering Model (iPeM). The iPeM has undergone initial testing in engineering projects and appears to be a promising approach to a mental framework for the future of engineering design.

17.1 Introduction – Five Hypotheses on Product Engineering

In the mid 19th century, Ferdinand Redtenbacher[2] defined design as being 50 % driven by scientific methods and 50 % by artistic work.

Redtenbacher's statement is still valid today. The design of technical systems is one of the most complex tasks a human can face. It is about coming up with technical solutions to social demands, using mainly creative abilities. This is one of the most difficult mental tasks, as it usually concerns complex systems with many different interactions and dependencies. Creative designers are among the most

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[2] At the time, Redtenbacher was a professor at the Polytechnische Hochschule Karlsruhe

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wanted experts in the technical world. Their impact on companies' profits is unfortunately often underestimated. Prince Philip of Edinburgh stated, ***"Innovation depends on invention - and inventors should be treated as the pop stars of industry!"*** Designer (and their inventions) are responsible for the future success of a company. They should be at the centre of product engineering, not a computer. The task is to learn and understand the processes of engineering design – the synthesis of artificial structures to fulfil specific functions – and to support humans with appropriate methods, tools and processes.

Since Redtenbacher, scientists in the field of design methods and design management have worked on ways to describe product engineering processes and the necessary methods.

During several years of working in industrial practice and scientific research in product development, the following approach and five underlying hypotheses were developed[3]. They form the basis for understanding the necessity to take a new and different view of product development and to see the designer as the centre of all design work.

The five hypotheses[4] are:

1. *Every product engineering process is* ***unique and individual*** *and primarily determined by the humans involved.*
2. *Based on systems theory, product engineering can be described as the transfer of an (initially vague) system of objectives*[5] *into a concrete system of objects*[6] *by an operation system*[7].

   One product has one and only one system of objectives and one corresponding system of objects.
3. *The central activity in product engineering is validation.*

   It defines the continuous refinement of the system of objectives and the product's success by continuous comparison with the achieved state of the system. **Only through validation can knowledge be gained**[8].

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[3] See (Albers 2010)

[4] For a more detailed explanation of the five hypotheses, see (Albers 2010).

[5] The system of objectives contains all information about the product, including interactions with its super systems (technical, socio-technical and social).

[6] The system of objects contains all documents and artefacts that emerge as (partial) solutions of an engineering process. It is only complete if the desired final state is accomplished. Besides interim results, such as project plans, prototypes, etc., the product is the centrepiece in the system of objects.

[7] The operation system can be seen as a fractal, socio-technical system that comprises all subprocesses, methods as detailed activities, and resources. The system of operation initially defines and continuously links the system of objectives and the system of objects.

[8] Validation is the only activity in product engineering that generates information, insight and knowledge. As opposed to verification and review activities, validation ensures conformity with the entire system of objectives (verification), and actually confirms that a product satisfies the demands of the market. Thus, validation and synthesis are the two fundamental activities of designing.

4. *Product engineering is problem solving; the objects that are created in an engineering process have to be described in reference to the system of objectives.* The initial state (objectives, available information, etc.), and the activities that lead to the final results can be arbitrarily unknown. Hence, the transformation process from objectives to objects can be considered a problem solving process.
5. *To be able to perform a function, a technical system needs interaction between its components. A function of a technical system requires at least two Working Surface Pairs, their connecting Channel and Support Structure, and two Connectors that channel the relevant influences of the surroundings into the technical system.*[9]
   A component by itself does not have any function.

In attempting to create an engineering framework that includes the ideas in these five hypotheses, three interconnected areas of relevance can be identified. First, the focus needs to be on methods and processes of engineering. This chapter addresses weaknesses of current, phase-oriented models and suggests overcoming them by using modelling engineering processes as sets of activities that transform objectives into objects. The second focus is on the transformation of objectives into objects. The widespread approach of referring to objectives as functions and the objects that fulfil those functions as components has to be overcome. A component by itself does not have a function. Third, the importance of validation will be emphasised. It is the most important activity in product engineering. It connects processes and methods of product engineering by focusing on the object system.

An approach is suggested that contains these three areas: the Integrated Product Engineering Modell - iPeM. It is based on systems engineering and moulds the findings of several branches of science into one comprehensive concept. It has proven to be flexible in initial implementations, and systematically brings together the two worlds of design methodology and design management.

17.2 Different Views on Methods and Processes of Product Engineering

In the domain of product engineering, scientists and companies in industrial practice work on the development and application of methods and processes for technical and socio-technical systems. Individuals will consider this challenge from one of two perspectives – either to suit specific applications or to form an integrated approach. Design methodology and process modelling are often considered as two interacting disciplines. However, only a few of their outcomes have proven

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[9] The hypothesis refers to the Contact and Channel Modelling Approach (Albers 2008)

to be practically relevant. One reason might be the isolated view of current approaches to methods or processes by designers or managers.

In many cases, models of engineering processes act as a representation for either managers or designers, but fail to integrate both views. The following sections underline the importance of using one approach that fits the requirements of both parties. Successful product engineering is a heuristic and creative process that depends on individual qualifications and the experience of all participating people – managers and designers.

Existing approaches[10] aim to methodologically support either designers or managers. Prescriptive models, e.g. sequential descriptions of engineering processes, do not usually support the description of iterative design activities or dynamically changing conditions that massively affect the progress of engineering. In consequence, planning and control of processes is difficult when using these approaches in industrial practice. This often leads to conflicts between product development and controlling.

In contrast, approaches that attempt to avoid detailed specifications of activities fail to support designers in their daily work. A flexible framework for management that expresses commonly applicable structures is not suitable for operative work in daily practice. Moreover, a well-balanced and clearly expressed structure of objects, objectives, activities and resources must be provided that allows the implementation of tools and methods by both managers and designers, who have a fundamental need to describe recurring solution patterns[11].

Management usually deals with measurable objectives. Objectives are made to fit the requirements of both market and competitive environments. They can also result from conditions arising from limited resources within a company. The types are interrelated and can pose risks to an engineering project if they are not dealt with.

Supervision and control of these risks and the achievement of objectives is – besides optimal use of resources – the major task for management. Models of product engineering processes thus have to provide a general overview of interrelations between objectives, resources and activities.

Even though carefully managing a process can prevent the need for major modifications of objectives during the implementation of a process, additional tools and methods must be provided to support designers in their daily work to create objects. Another goal is to maintain constant feedback and communication between designers and management, because a designer's perspective on modelling engineering processes is centred on operative support in daily activities. Studies in industrial practice show that the instable and dynamic nature of processes

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[10] For example, VDI 2221, Stage Gate Models, V-Model, and others. For a more detailed overview, see (Meboldt 2009).

[11] The manager and the designer can be the same person. The two worlds are not contrary they are just different.

calls for a high degree of flexibility, and that many models are not applicable to real design cases.[12]

Whether engineering products are newly developed or designed to improve existing solutions, the processes of product engineering, to a large extend, follow recurring activities and patterns. Focussing on activities rather than phase models provides a more detailed impression of complexity and important dependencies. Activities that require organization and management can be described in models of product engineering processes. Methods and tools have to be provided to support these activities. A systematic and holistic view is important to understand these interdependent activities under changing boundary conditions – and to support engineers in both management and design.

Considering both perspectives, activities can be generally described from two levels of abstraction, each with a specific focus and field of application: A macro-logic view of activities of product engineering provides a general overview for management; and the more detailed view of the micro-logic provides steps for problem solving in design[13].

Macro-logic activities of product engineering describe operations typical of product lifecycle stages. However, they are not assigned to any chronological sequence of operations, but rather have to be individually applied according to situation-specific requirements or in iterations. From initial activities of project planning and controlling, to final analysis of utilization and decommission[14], they should be described as active operations that produce both objects (physical objects as well as information in general) stored in the system of objects, and new objectives in the system of objectives. The macro activities of product engineering are generic, so they can be fitted to existing process models for use in industrial practice. Because of their generic character, it is not yet possible to effectively assign tools and methods of product engineering to supporting the design aspects. It is helpful to set up a more detailed structure that acts as a linking guideline for designers to support orientation, organization and management. The detailed conduction of any such macro-activity can be seen as a problem-solving process and can therefore be modelled as activities of problem solving.[15] For each problem solving activity, it is now possible to assign suitable methods and tools according to the respective macro-activity of product engineering. Together, they span a matrix of activities that can be used as a structured guideline for designers to transform objectives into objects – and thus to support the designer's perspective on engineering processes. In a specific product-engineering project, the individual

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[12] (Birkhofer 1991, Mebold 2009)

[13] See also (Daenzer und Huber 2002, Lindemann 2005).

[14] For a detailed overview on the macro activities of product engineering, see (Albers 2010a).

[15] This understanding of activities in the context of modelling product engineering processes was surveyed by (Hubka and Eder 1996 and Albers 2010). They propose that engineering design is a rational cognitive activity that can be deconstructed into smaller steps at individual levels of abstraction to match a design problem.

sets of problem solving activities become a unique chain of activities and thus a unique problem-solving process for the project. Recurrent solution patterns of different engineering projects can be gathered to provide assistance, for example, in the form of operation guidelines for planning future design projects, which in turn reflects the management perspective.

Considering different views and thus different levels of activities in product engineering provides an opportunity to model processes in a way that is detailed enough to support designers, and that can be generic enough to provide support for management. Both are important for the successful transformation of the system of objectives into the system of objects.

17.3 Product Engineering is the Transformation of Objectives into Objects

In considering product engineering as a problem solving process, design activities do not follow a sequential progression from function structures to embodiment design[16].

Moreover, designers go through a set of activities that merge synthesis and analysis. The main purpose of conducting these activities is to transform objectives into objects – and ultimately successful products on the markets. To express these objectives in technical terms, designers often refer to functions that must be fulfilled. Experiences from industrial practice show that design methods that focus only on the development of product components – the synthesis of single objects – fail to integrate important functional aspects, since they cannot be used to reflect the dependencies of an interacting technical system[17]. Interactions between components make a technical system work. Thus, it is even more challenging that today's design practice often still focuses on isolated components without sufficiently considering their implementation in a system.

One component on its own does not have a function. Moreover, function and form depend on each other and emerge in iterations, including in many validation activities. Therefore, it is not possible to design form without simultaneously considering function. In turn, the implementation of functions into a technical system always requires the design of the form. Consequently, modelling the function and form of a technical system calls for a common modelling approach for the system of objects and the system of objectives during all activities of product engineering. The Contact and Channel-Connector-Approach (C&C^2-A) provides a systematic approach to support designers in analyses and synthesis of technical system.

The underlying approach is that the performance of functions always requires interactions between a system's components and its environment – one component

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[16] (Pahl and Beitz 2007)

[17] (Birkhofer 1991, Jaensch 2007)

itself cannot perform any function (see Hypothesis V). These interactions take place in Working Surface Pairs (WSP), which are interconnected by Channel and Support Structures (CSS). These elements are fractal, i.e. they can be modelled similarly at different hierarchical levels. Functions can always be ascribed to the dependencies of WSP, their connecting CSS and Connector elements, which include a system's relevant surrounding influences from the model's perspective. Objectives, in terms of functions, can thus be directly linked to the form of the objects to be designed.

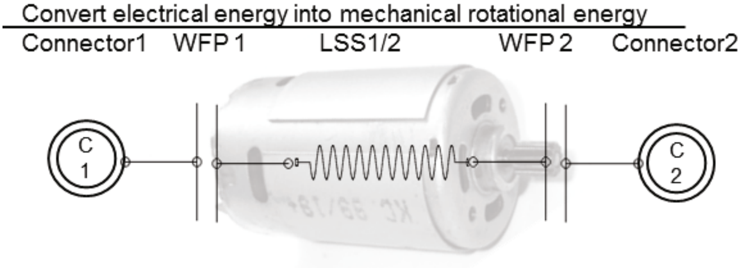

Fig. 17.1 C&C^2 Model of an electric motor

The market value of a product refers to the quality of the implementation of its functions. A designer's main task is to design WSP and CSS of interacting components instead of volumes and surfaces of single parts. Creativity and experience must still be taken into account, but a systematic view of these aspects determines successful design, and can open up new possibilities for creating new solutions. To maintain an effective and thus successful transformation of objectives into objects, validation activities are essential.

17.4 Validation

"Develop the right product right!" – This challenge can be managed only if validation is assessed under two aspects simultaneously: ensuring both the correct state of the product and the correct activities to engineer the desired product.

Validation has been badly neglected in research on product development processes in the past. A large number of researchers concentrate on the "early stages of product development" in topics such as product definition and profile detection. Meanwhile, only minor importance is being attached to validation, the comparison between the achieved status in the development process, and the objectives, boundary conditions and relations described in the system of objectives. Validation is not limited to physically testing prototypes but includes comprehensive simulation (e.g. virtual reality) activities as well.[18]

Conversely, in engineering practice, validation is definitely the central activity as it contributes decisively to the generation of knowledge and ultimately to the success of a product development project. In addition, it is by far the most expensive and time-consuming activity in the whole product engineering process. The resources that automotive companies[19] assign to testing and simulating vehicles or their subsystems[20] are enormous and determine the development budget. Validation should thus have a prominent role in the further improvement of product engineering processes[21].

New developments in the field of automotive engineering, especially in drivetrain technologies and new drives with the growing amount of mechatronic systems in all areas, lead to a further increase in the impact of validation activities on the product engineering process. Implementing more and more previously uncommon technologies (e.g. electric drives or hybrid drivetrains), existing expertise loses its value, even in the field of validation, as it cannot simply be applied to new technologies. At the same time, the technical systems that have to be validated gain in complexity. Almost all modern technical products have a “mechatronic character”. Therefore, it is extremely important to provide methodological support for systematic testing, combined with development processes that allow a high degree of interdisciplinary method integration.

As an example, the IPEK X-in-the-Loop Framework[22] provides a holistic and integrated development and validation framework for powertrain systems. ‘X’ is the Unit Under Test (UUT). In addition to established Hardware-in-the-Loop approaches, the UUT can be a real prototype (for example, starting from property analysis of friction facings, up to the complete vehicle) as well as a virtual prototype. The XiL Framework can be used for validation activities throughout the whole process of automotive engineering. It allows designers to focus on interactions between the vehicle and its driver, its environment as well as its subsystems and interfaces at different levels of detail and abstraction. The XiL Framework is scalable and generic, and applicable to the development of other mechatronic systems as well.

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[18] See (Albers 2010b)

[19] The focus on automotive engineering is only an example. The statements are equally applicable to other fields of engineering.

[20] This includes both hardware testing as well as virtual testing in complex simulations.

[21] This is emphasized in the 5 Hypotheses.

[22] See (Albers 2010c)

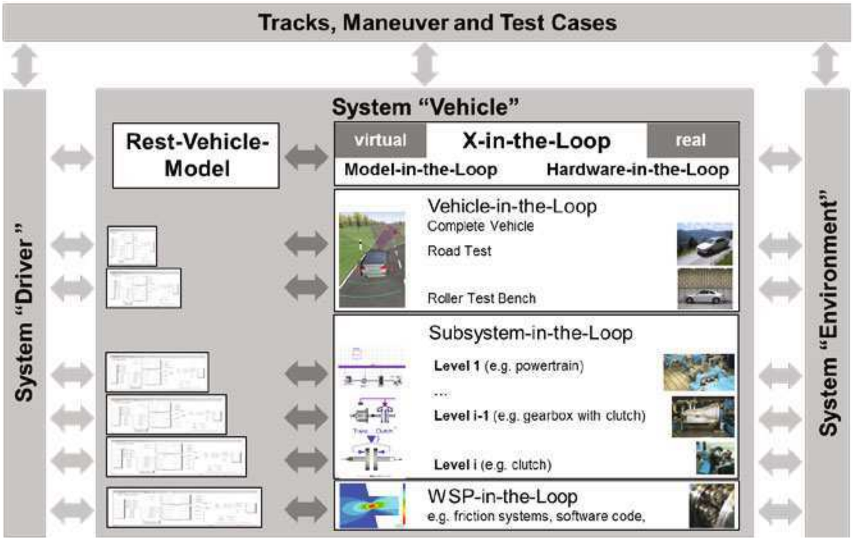

Fig. 17.2 X-in-the-Loop Framework for powertrain systems

17.5 Introducing the Integrated Product Engineering Model iPeM

As per the statements in the first three hypotheses, a model is needed that:

- supports both management and designer perspectives
- contains *who* is performing *which activities* at *what time*
- provides tools and methods to generate information and engineering results
- assigns the central role to the activity of validation
- serves and supports the human in the process, as the human is the centre of product engineering.

Product engineering activities are based mainly on systematic, iterative and creative work. Their course is not deterministic, as the final set of objectives can only be derived gradually from partial solutions and environmental influences on the design activities. The heuristic problem solving character of engineering processes is contrary to the desire for exact planning in advance. The above-named aspects motivate the composition of a generalized framework for engineering processes. An integrated approach should capture all facets of product engineering in one uniform, consistent model. As a meta-model, its generic character should allow arranging a model of activities to an individual process model that reflects upon challenges of problem solving processes in engineering practice.

The Integrated Product Engineering Model iPeM provides this general framework[23]. It can be used to encompass and support individual, complex product engineering activities. The variable model integrates design support for navigation and provision of methods and tools, on the one hand, and managerial purposes, such as deriving decisions in ambiguous situations, on the other.

The iPeM allows problem-oriented process control, with systematic focus on activities that relate to both objectives and objects. Methods and tools for both management and design can individually support every activity of a process. The iPeM aims to depict the interdependencies of engineering activities, methodical support and process management. Incorporating a system of objectives, an operation system and a system of objects into one consistent model, a flexible representation of activities of any individual design process that includes different perspectives on engineering design can be derived. Contrary to strictly stage-oriented models, this approach starts from the hypothesis that any engineering process is unique. Individual sets of activities with particular deliverables can be arranged according to specific requirements of design practice. This provides a flexible framework for coping with the challenges of modern design practice.

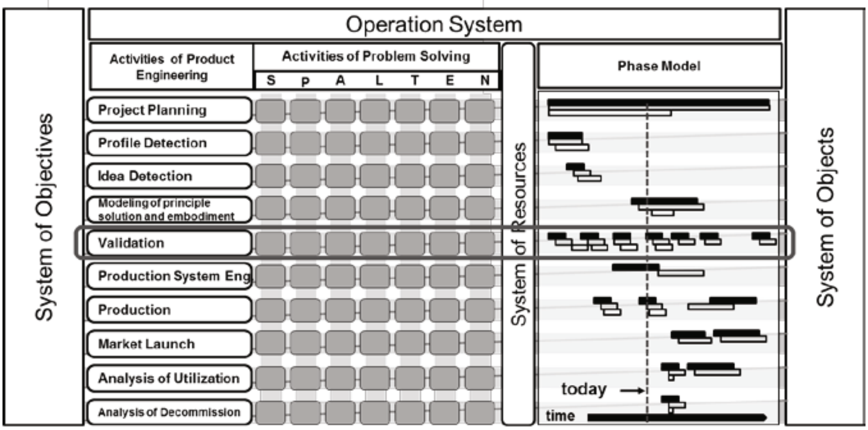

Fig. 17.3 Layout of the iPeM meta model for product engineering processes

17.6 Conclusion

The future will be driven by the great new opportunities created by new technologies, materials and even new disciplines of engineering. It is not currently known exactly what the opportunities are going to be, but it is known that a rising number of options will also make the world of engineering more complex and far more

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[23] see also (Albers 2010a)

challenging than it is today. Apart from all this, it is known for sure that humans will be the centre of product engineering.

In order to cope with the future challenges, new ways of engineering are needed today. The ideas and the approach described here include three main aspects:

Overcoming phase-oriented sequential engineering: product engineering needs to be seen as sets of activities, not as a series of different phases.

Overcoming thinking in components and their functions. A component does not have a function. Only if designers learn and train to think of form and function as two inseparable elements can important functional and systemic relations be taken into account.

Validation is the most important activity in product engineering: Only through validation can information be turned into knowledge to ensure that the right product is being developed and that it is being done the right way.

The future of engineering design and engineering methods will be exciting but challenging. The essence is thus, “Don’t wait for it; design it today.”

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Chapter 18

Summary - Holistic Ways to Supply, Extend or Replace Design Methodology

H. Birkhofer

A large group of authors puts the whole approach of Design Methodology on the test stand. By formulating holistic approaches the existing Design Methodology is extended with regard to the design-object and/or the respective processes. Additionally, the extension with methods from other science areas or even alternative development methods is considered.

18.1 Object-related extension of Design Methodology towards a development methodology for Product Service Systems

The first subgroup of authors widens the area of the design object towards services, addressing the area of Product Service Systems (PSS), increasingly researched over the last ten years.

In his contribution "Boundary conditions for a new type of design task: Understanding product/service systems", *McAloone* discusses the framework and influencing factors required for PSS development to achieve a better understanding for PSS. Even though many questions remain and a holistic method for PSS design is not complete, the author determines six typical design characteristics, derived from empirical research. Competencies and disciplines describe the abilities and activities required of manufacturers over the whole life cycle. Contributions have to change from delivery of artifacts to creation of value for the user. This results in new production forms that include work-related contributions and user-driven innovations. To be accepted by users, PSS needs to offer distinct advantages over physical (tangible) products and specifically use the variety of executional interventions. Finally, the development of PSS requires a reconsideration of the dominant quality goals of manufacturers in the creation of value for the customer. This results in considerable, somewhat drastic changes in the core business of manufacturers. These changes require a new and comprehensive view of all company departments over the entire life cycle and all activities to create value for multiple stakeholders.

In "Product Service System Design and Beyond" by *Sakao* the fundamentals of PSS are first explained. The differences between PSS design and traditional engi-

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neering are outlined. The differences are found in the output, with its physical products and services; the provider, with their organizations and operations; and the customer/user as the receiver of PSS. PSS research can be categorized into three areas. One area is the modeling of different PSS. A second area addresses the development of a PSS methodology. The third area regards the identification of PSS potential for manufacturers and stakeholders. Future PSS research could target the development of a method and tool supported PSS design process. Additionally, there is the need to formulate propositions of how to adapt existing organisational structures to PSS design and how to anchor the PSS mindset as the main requirement within employees, the organisational units and the entire company, including the corporate culture. So far, the request for integrated development of technologies and business models has not been addressed in a separate research area. However, it becomes more important in PSS development. The development of technology is fundamental for company wealth and an incentive for many product innovations. Due to the long-term nature and the relevance of technological progress, the development of business models has to be integrated. Only in this way can competitive advantages over threshold countries be achieved. This integration has barely been investigated but presents a challenge to research on PSS development.

18.2 Process-related extensions of Design Methodology towards a methodology of computer-aided planning and development of activities

The tremendous influence of CAX-technologies on design practice and the way of integrating computer aided tools or even combining them with Design Methodology is addressed by two authors.

In their contribution “Open product development”, *Riitahuhta et al.* establish that a General Design Theory does not yet exist, and so the scientific fundament of a Design Methodology is still missing. The author proposes a pragmatic approach for a methodology derived from the analysis of real development projects in industry, mainly for products with many variants. This methodology significantly widens the range of processes that need to be considered. Additionally, it requires the development of business cases and technologies that include a company’s success as a decisive element. This superior design process is based on the Open Innovation Approach and consists of three design phases. In proactive, strategy-based construction of product development facilities, the product architectures are determined and documented in the Company Strategic Landscape. It shows the relations between the product architecture and the delivery process, which have to be synchronised. The configuration of products and product families is computer-aided to detect the impact of the standardisation of items, engineering knowledge, sales, customer satisfaction, costs and total lead times. It is also important to document the variety in products and product families, and to determine which factors have a negative effect on the production systems and processes. Established methods and known technologies of knowledge management are pragmatically implemented in this approach.

In "Managing virtual product creation", *Anderl* sketches a comprehensive concept of a virtual product creation process with continuous computer support. It is a holistic approach based on classical Design Methodology and includes all phases of virtual product creation. It relies on the three core technologies "application software systems", "digital representation of development results" and "powerful communication technologies". The origin of this approach is a comprehensive life cycle approach whose specific phases are described by a workflow and a set of activities. Depending on the intention of the life cycle factor (business administration, ecological sustainability, information technology), different planning goals and specific dependencies between material flow and information flow unfold. The product creation phase contains the workflows of product planning and product development, which are complemented by other workflows, such as analysis, simulation and optimisation. The specific workflows are controlled by planning and control methods and integrated into the workflow management. All results are represented in product data and evaluated and released in a release management. If changes during the product creation process become imminent, an existing workflow can be changed arbitrarily but a specific change workflow has to be activated. With this comprehensive workflow concept, the status of product creation can be retrieved at any time and even be quantified with the help of progress indicators. For this application, progress monitoring is suggested and maturity management must be installed. With these additions, conclusions on the project status obtained can be drawn for future proceedings. This requires the integration of components and performance testing to receive quantifiable results.

18.3 Additions to Design Methodology with holistic methods derived from other science areas

Two authors add new methods derived from other science areas to the existing Design Methodology that can be used to carry out specific tasks.

In the contribution, "Systems engineering versus Design Methodology" from *Lindemann*, findings from Systems Engineering are adapted for use in product and process development. Structural complexity of products and processes can be analysed and optimised with the help of graph and matrix methods. The Multi-Domain Matrix (MDM) approach represents structures of different elements as objects, processes or stakeholders and visualises their relations in a strength-based graph. Structural dependencies become more transparent and interpretable, which leads to reasonable and comprehensible decisions based on appropriate measures. The author demonstrates how this method's power becomes obvious if several types of elements and the diversity of relations between them is represented. Analysis of the requirements of a hotel laundry service shows how the structural criteria can be interpreted and used to analyse requirements and support decision-making. The problems of isolated knowledge transfer are shown using the example of knowledge identification. Only the interlinked modeling of knowledge units, knowledge carriers and receivers can improve the quality of knowledge transfer because the focus can shift to the focal points of the transfer. Cost estimations of mechatronic products in the early phases of product development are aided by MDM, as it helps to clarify the connection between cost and the degree of cross-linking of tasks and inventories, thereby determining cost factors. Robustness and flexibility of the entire process can be improved. In total, the way of displaying structures in MDM is universally applicable and supports designers in early development phases so they can identify appropriate decisions for further processing and the starting-points for optimisation.

In “The autogenetic design theory – product development as an analogy to biological evolution”, *Vajna et al.* use analogies with biological evolution to find the best solutions for changing requirements and boundary conditions. The basic principle of “trial and error” is applied to solutions where chromosome sets are compared to the original solution and evaluated for their performance. Self-similarity of solutions and unpredictable behaviour of systems according to chaos theory are premises of the Autogenetic Design Theory (ADT). ADT uses a process model based on target functions, a preliminary solution space and starting conditions, boundaries and constraints. In the four creation steps selection, recombination, duplication and mutation new solutions are generated and evaluated for their fulfilment of optimisation goals of the target function. After each evaluation and selection step, the solution space and criteria are updated to account for the dynamic of the solution generated. ADT and Design Methodology differ in the definition of the solution space. In ADT, all solutions that are not found within the prohibited space are allowed. Their performance is determined in the subsequent evaluation. The ADT product model is based on the extended feature model, which, in compliance with the methodological view, describes a product by its design parameters (chromosomes). They correlate with the product properties that correlate with the requirements and boundary conditions. Due to the comparison, the performance of representatives of each solution generation can be evaluated and the best ones selected for the next step.

18.4 Alternative design methods with new paradigms

Two authors go so far as to question traditional Design Methodology at least in some basic principles and present others methods for the development of products.

Badke-Schaub et al. start their article “Towards a designer-centred methodology - descriptive considerations and prescriptive reflections” with a history of goals, approaches and successes of method usage in design practice. The deficits and shortcomings of renowned design methods are highlighted in a literature review. The main criticisms target the methods' unclear or non-validated performance, their insufficient description for practice, the barriers to permanently and beneficially use them in specific design processes and the unsolved question of how to implement flexible method usage. The authors categorise design processes into routine processes and non-routine processes. In routine processes, standard methods can be applied. In non-routine processes, special cognitive mechanisms of designers have to be applied to reduce the associated uncertainty as quickly as possible. An interview study revealed three sources of uncertainty: The designer's individual preferences and restrictions, the social context of work and uncertainties in the approach that could be taken to solve design tasks. Different strategies to control uncertainties were derived from the interviews. Designers need to choose the strategies according to each specific case. The goal of the "new" Design Methodology should be to support this personalised "design thinking" as an individual, problem-adjusted solution method, especially in non-routine situations. This person-centred methodological approach appears to be effective in supporting the designer as an individual. However, it requires a thorough empirical survey and is far from being elaborated enough to be called "designer-centred methodology".

In their contribution "A new perspective on Product Engineering overcoming sequential process models", *Albers et al.* propose that design is one of the most complex tasks for an individual. From this understanding, three hypotheses are formulated to create a new view on product development. The initial approach is to integrate the different perspectives of designers and management, which are accounted for by modeling of micro and macro-activities refering to one another. Micro-activities represent the problem solution process of designers. Macro-activities describe management's perspective on product life cycle stages. Within the micro-activities, it is important to highlight the simultaneous examination of function and form with the help of a working area and a working surface model. Validation plays a central role within the development process. It is the decisive source of findings in the process. Validation is a kind of comparison of requirements and product properties and ranges from simple calculations to complex hardware-in-the-loop approaches. From these findings, the Product Engineering Model has been developed. It supports management and designers in their activities and provides methods and tools to generate solutions and information. It accounts for the particular relevance of the validation of product development and therefore adequately supports human thoughts and actions with its creative and heuristic nature. Finally, the phase-oriented, sequential work sequence of methodical design will be overcome, the integral thinking in functions and components will be promoted and information and knowledge acquisition in design work will be improved by validation.

18.5 Results and recognitions

Some of the seven authors justify their proposals with deficits determined of Design Methodology in practice (Figure 18.1). Others were motivated by findings from adjacent or even unrelated scientific areas.

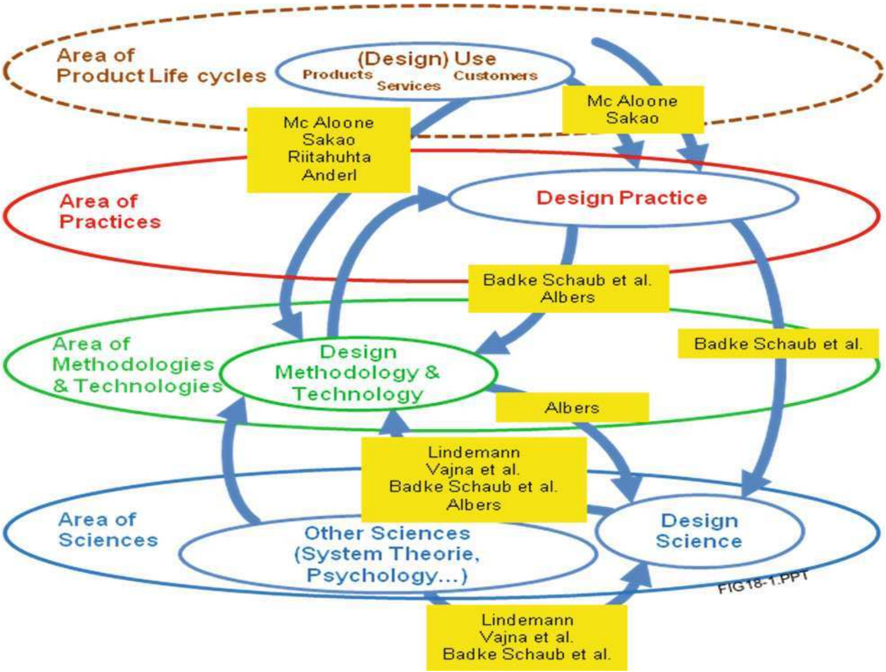

Fig. 18.1 Categorization of the contributions in this section "Holistic Ways to Supply, Extend or Replace Design Methodology" according to their research approach

The entries are remarkable for:

- Their orientation on current and future challenges in design practice, e.g. the extension of PSS
- Their consideration, even integration, of other "design processes" into companies, e.g. the development of business models and technologies into a holistic development method for an entire company
- The significantly stronger integration of computer tools and software tools whose abilities are only modestly reflected in classic Design Methodology
- The trend towards automated or at least algorithm-supported design that transfers development work from humans to computers

- The strong focus on the designers as individuals whose thinking and actions cannot be described with sequential schedule models or equally obligatory, de-individualised procedures.

Overall, the propositions indicate that classic Design Methodology has deficits in supporting current or even future development work that necessitate a substantial reformation.

Part III
General Reflections on Design Methodology

Chapter 25

Herbert Birkhofer

Summary - General Reflections on Design Methodology

Chapter 19
What Designers Can Learn From Leonardo, an Ingenious Artist, Scientist and Engineer

H.-J. Franke[1]

Leonardo da Vinci was one of the greatest geniuses of humanity. Like no-one before and surely no-one since, he combined nearly all the knowledge and many abilities of his time, having brilliant ideas and concepts for the future. Leonardo's special thinking and methods correspond with the work of designers and scientists, helping them towards greatness. Some conclusions are given on useful learnings from Leonardo. His works and abilities as an artist, (natural) scientist and engineer are discussed: we can still learn from his thinking and methods.

19.1. Leonardo's Life

Fig. 19.1 Leonardo da Vinci 1452 - 1519
It is estimated that this self-portrait shows Leonardo at the age of about 58.
His painting teacher was Andrea del Veroccio (1435-1488) in Florence

In his trained profession as a painter, Leonardo created some of the most important works of fine art. As a self-taught person, he discovered laws of nature,

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worked as a philosopher and mathematician, and developed fascinating ideas and concepts as an architect and engineer.

The powerful people that he knew were very important for his life and work, for example, Lorenzo de Medici (Florence), Cesare Borgia (Roma), Ludovico Sforca - "Il Moro" (Milano), Cardinal Giuliani II de Medici (Roma) and the Kings Ludovico XII and Francis I of France. He was strongly influenced by his friendship with the mathematician Luca Pacioli in Milan and the anatomist Marcantonio della Torre in Pavia. It is assumed that he met Niccolo Machiavelli in Imola.

19.2. Some Thesis on Abilities, Skills and Methods in Art, Science and Design

Some of Leonardo's works are summarized below, and sorted into the categories art, science and design (Figure 19.2). They correspond to general methods and skills (Figure 19.3).

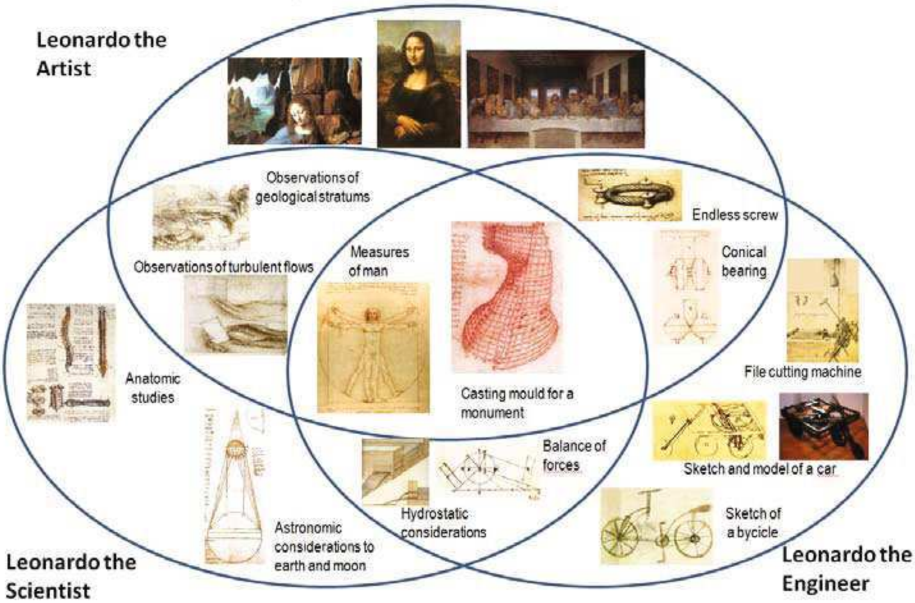

Fig. 19.2 Some examples of Leonardo's works, sorted into scientific, artistic and engineering classifications

Each field in art and science needs special methods and skills. However, there are commonalities, as shown in the Venn-Diagram in figures 19.2 and 19.3.

This systematic pattern can help generate ideas for abilities, skills and methods that can be taken from Leonardo and applied to today’s business.

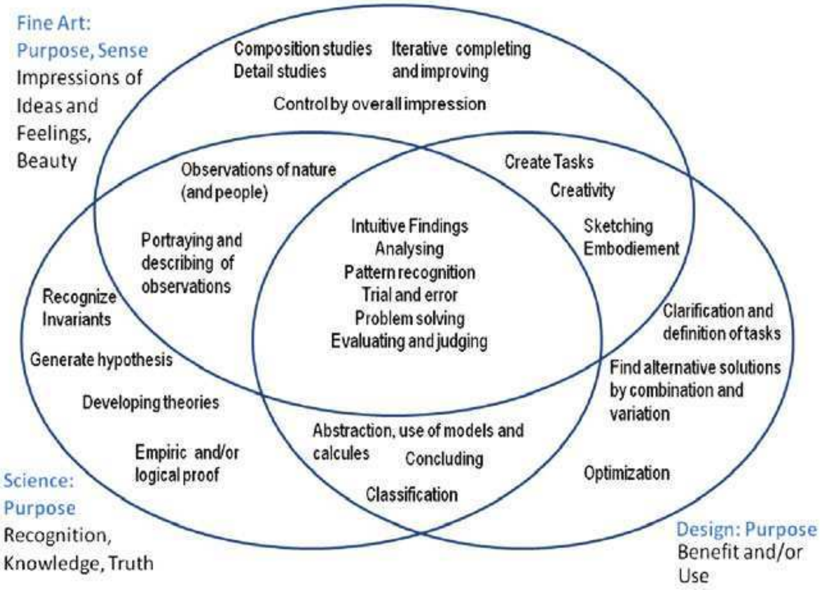

Fig. 19.3 Methods used by artists, scientists and designers, correlated with figure 19.2

19.3 Leonardo: a First Man of the Modern Era

For his time, Leonardo was exceptionally open-minded and fearless in his generation of new ideas and works. Some quotes by Leonardo give witness:

> Science is the child of experience.

From the original Italian: *"La sapienza è figliola della sperienzia."*[2]
This is a big step toward the modern understanding of science.

> No effect in nature is without a rational reason; recognize the rational reason, and you do not need experiments.

From the original Italian: *"Nessuno effetto è in natura sanza ragione; intendi la ragione e non ti bisogna sperienzia."*[3]

One hundred years before Galileo Galilei and two hundred years before Isaac Newton, Leonardo was a shining light in modern scientific and logic thinking.

Leonardo's wide-ranging observations in optics, mechanics, hydraulics, geography, anatomy and other sciences impressively prove his urgent desire to understand nature. This understanding still lively and valid as the CEO in my first in-

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[2] Source: Aforismi, novelle e profezie

[3] Source: Diaries and records

dustrial function as a designer told me in 1977: An engineer needs a "sound physical image of the universe" (in German "ein gesundes physikalisches Weltbild").

To understand nature and physics is up today one of my most believed ideas of engineering.

19.4 Useful Methods and Skills of Leonardo

Leonardo showed extreme diligence and fortitude in his work. He worked on some problems for more than twenty years.

Designers need the ability to work sustainably at a problem when up against many and various odds.

Leonardo, when painting, would often switch between a detailed view to an overall view and back.

When painting the "Holy Communion"(Figure 19.4) in Santa Maria delle Grazie in Milano, he often used to go to the middle of the church and sit sometimes for half an hour and critically consider his work, then go back and start to improve the picture in detail.

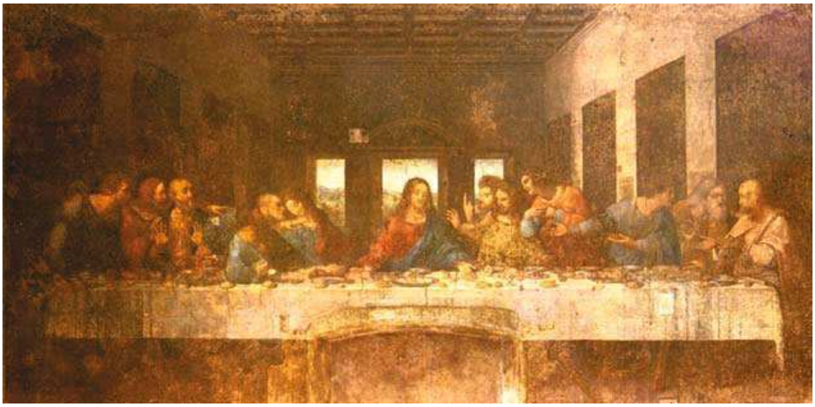

Fig. 19.4 The Holy Communion

For mechanical designers, especially in the phase embodiment, it is also very important to consider the total solution in iterative steps, to recognize problems, e.g. disturbance effects, and difficulties in machining and assembling, and improve the recognized weak points.

Leonardo made observations and took notes extremely patiently and thoroughly, in writing and as sketches, in his famous diaries of interesting human, natural, geological and physical subjects. It led him to new ideas and concepts.

New ideas for new products need observations of human living, nature, technical systems and knowledge bases such as books, magazines and the internet.

Perhaps Leonardo's most important ability that designers can learn from was his brilliant problem solving by sketching. Based on his exact observations and an incredibly spatial imagination, he could bring his "mental virtual products" to life by sketching them as "understandable models" for communication, for example, with clients or artisans.

Sketching is still faster and much more creative than modelling by CAD.

Sketches are often very important to finding new ideas (Figure 19.5), explaining principles (Figure 19.6) or understanding difficult physical problems (Figure 19.7).

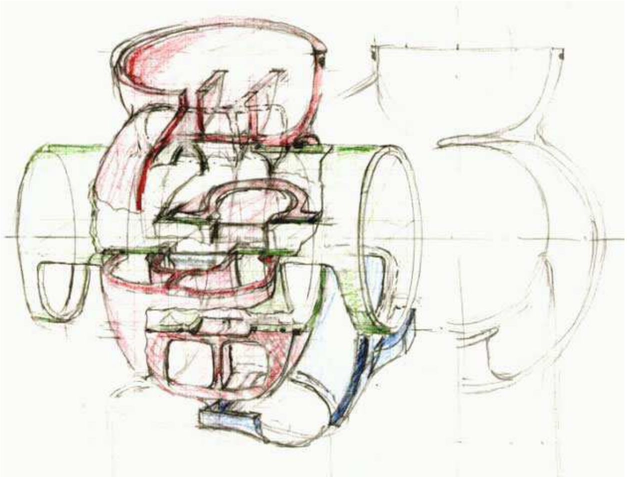

Fig. 19.5 Casing for a patented reactor cooling pump

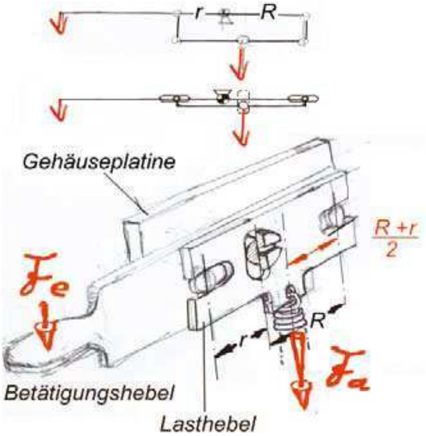

Fig. 19.6 Principle and conceptual solution for a differential lever mechanism

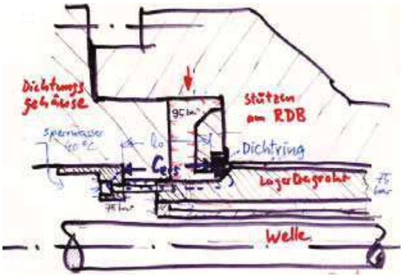

Fig. 19.7 Sketch for modelling and understanding of temperature distortion problems in a primary coolant pump

19.5 Leonardo's Dream of Flying

Leonardo had an amazing ability to understand problems and to solve them by association. For example, he had ideas and understandings about the flow in the heart by drawing analogies to observations of hydraulic sluices. Another example is his observation of birds over many years. He wrote, "Birds are flying machines" (Figure 19.8).

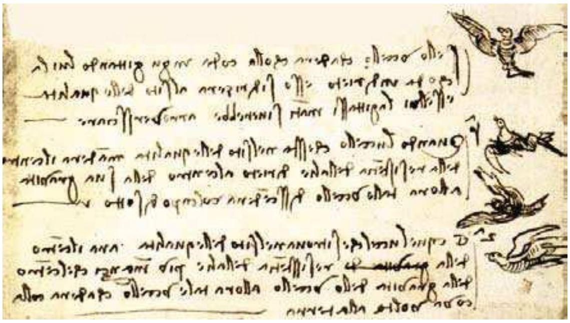

Fig. 19.8 Notes and sketches of Leonardo

More than 450 years later the first successful flying machine was the glider with fixed wings made by Otto Lilienthal in 1891 (Figure 19.9). Like Leonardo, Lilienthal observed birds, in this case storks, to find the right solution for flying.

Fig. 19.9 Otto Lilienthal, 1891. Source: http://de.wikipediaorg/wiki/Otto_Lilienthal

The first flight (145 m) with bird-like wings similar to Leonardo's sketched solutions of an ornithopter was carried out in September 2010 by Todd Reichert and colleagues at Toronto University (Figure 19.10).

Fig. 19.10 Ornithopter of Todd Reichert in Toronto 2010, source: www.stern.de/wissen/technik/ornithopter-rekordflug-wenn-der-mensch-mit-den-fluegeln-schlaegt-1608406-49375235c2f0c8d4.html

We can learn problem-solving by associations and lateral thinking from Leonardo. Leonardo was a pioneer of bionics.

19.6 Conclusions

Without doubt, Leonardo is one of the most astonishing geniuses of humanity.

He had a "modern" understanding of science and many extremely useful abilities and skills that are still valuable to people of the 21st century.

Designers can especially learn from Leonardo to be open-minded, to patiently observe, associate and combine knowledge from different fields, to develop 3-dimensional imagination, and to sketch quickly and precisely.

Acknowledgments I have known Prof. Dr.-Ing. Dr.-Ing. e.H. Herbert Birkhofer for more than 36 years. He is a good friend, a helpful colleague and an internationally recognized expert. For the following years I wish him and his wife health and luck, always good ideas and more time for his family and his hobbies.

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Chapter 20
"Design … but of What"?

M. Cantamessa[1]

Abstract Researchers in the field of design are often challenged by outsiders with the question "*design… but of what?*", as if their insights, research results and proposals were specific to a given field of human activity. This misinterpretation is easy to dispel if one looks at the vast and growing effort in disciplines both technical and non-technical, to bring greater rationality and rigor of method to design. The paper has the objective of discussing issues that are likely to challenge design researchers and practitioners in the near future, based on both the diffusion of design-related concepts and on the growingly complex nature of artifacts and of the context in which they are developed.

20.1 Introduction

In 1969, Herbert Simon brought to the world what can be considered to be a groundbreaking statement:

> Engineers are not the only professional designers. Everyone designs who devises courses of action aimed at changing existing situations into preferred ones. The intellectual activity that produces material artifacts is no different fundamentally from the one that prescribes remedies for a sick patient or the one that devises a new sales plan for a company or a social welfare policy for a state. Design, so construed, is the core of all professional training (Simon 1969).

The claim that design or – perhaps more appropriately, "designerly" activity (Cross 1982) - spans virtually all areas of human endeavor, and that this hints to an underlying and common "Science of the Artificial" is something that still can cause some eyebrows to be raised. In fact, it is the personal experience of many researchers in the field of design to be questioned by outsiders asking: "*oh I see, you are working on design… but of what?*", as if design-related insights, results and proposals had to be specific to a given field of human activity.

The objective of this paper is to share a few reflections on this issue, some forty years after Herbert Simon's statement. Specifically, it will attempt to discuss – though certainly not to fully answer – two questions that the author considers to be highly relevant to design activity today and in the coming years.

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1. Is it true that, following Simon's suggestion, concepts related to design have diffused beyond engineering and spread into an increasing number of fields?
2. What is the social, economic, and technical context within which design activity occurs today? Is it different from forty years ago?

The following two sections of the paper cover these apparently disconnected questions, and are followed by final conclusions on the roles and issues that are likely to challenge design researchers and practitioners in the near future.

20.2 The Diffusing Concept of Design

Most readers of this volume are likely to have their academic roots in the fields of engineering design, product design, or architecture, and to have firstly approached the topic on textbooks that – though aimed to a general understanding of design – roughly shared the same roots (e.g. Pahl and Beitz 1977 and following editions, on the side of engineering design). Over the years, the concepts shared by the design community have undoubtedly been picked up by researchers and practitioners from many different fields and can be nowadays be found in areas such as service design, software engineering, and the like.

A simple exercise in bibliometrics can provide some quantitative evidence supporting this impression. Queries have been performed on the Thomson-ISI Web of Knowledge database, in order to evaluate the degree with which design-related papers appear in a wide variety of scientific areas, and to highlight related trends. Specifically, design-related papers have been identified by searching for publications having the following phrases in the title

"design theory*" OR "design method*" OR "design process*".

The papers have then been grouped by 5-year time intervals over the 1970-2009 horizon. Per each interval, the number of papers relevant to each scientific discipline reported (or "General Category", using ISI terminology) has been counted, and two well-known concentration indices (Herfindahl and Gini) have been computed. Figure 20.1 clearly shows that the concentration of these design-related papers is progressively decreasing, which implies a progressively lower share of papers coming from the disciplines that are "traditionally" relevant to design, such as engineering, and a higher fragmentation across other disciplines.

So, it appears true that design-related contributions are diffusing beyond their original academic domains and therefore have the potential of becoming a common meeting ground of the Sciences of the Artificial that Herbert Simon had been a prophet of. For this to happen, it is of course important that not only keywords are shared, but also key concepts and approaches, and this simultaneously can be seen as an opportunity and a responsibility for the design community.

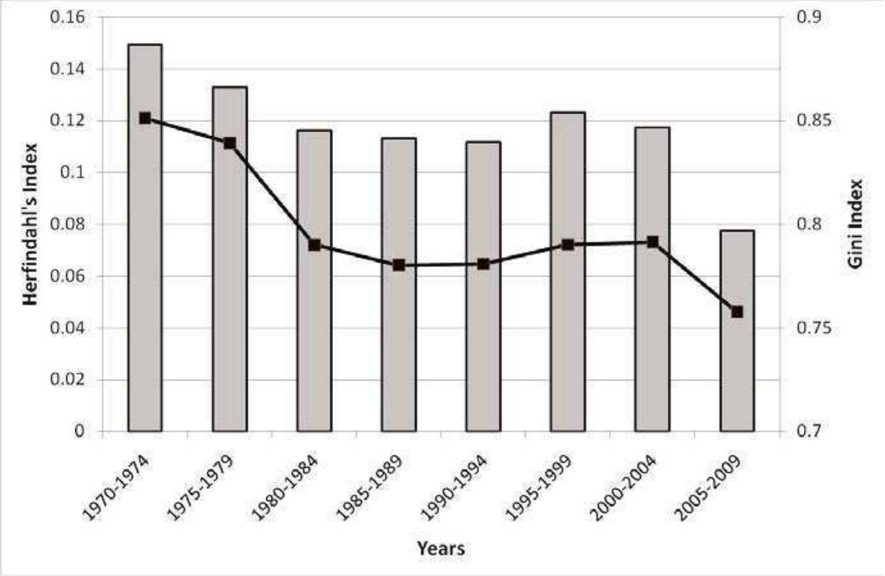

Fig. 20.1 The progressive diffusion of papers dealing with design theory, methods or processes in academic domains (lower values of Herfindhal’s index – depicted with bars - and Gini’s coefficient – represented with a line - imply a lower concentration in subject areas). Source: computation on data obtained through Thomson-ISI Web of Knowledge

20.3 The Changing Context of Design

Forty years ago, design in industry occurred in a typically Fordist environment, with a clear separation between firms, which were generally characterized by a high degree of vertical integration or were linked to one another by well-defined customer-supplier relationships within their supply chains. Typically operating within the paradigm of mass production, the focus was on flooding the markets with affordable manufactured goods. This allowed firms and customers to operate at a distance, without too much attention being paid to “customer needs”, while the whole process occurred within relatively long product life cycles. In a way, the whole process was product-centric (figure 20.2, left), with a strong emphasis on the products being designed, manufactured and bought. The “experience of use” by the customer was certainly considered, but did not have a key role in the process.

The subsequent post-Fordist scenario was typical of the ‘80s and ‘90s and has been very well captured by a number of studies, among which Womack et al. (Womack et al. 1991) and Clark and Fujimoto (Clark and Fujimoto 1991) are probably among the best known. These decades were characterized by intensifying competition in the mature markets of the developed world. Slow economic growth and maturing products made it necessary for firms to capture the attention of customers, by offering products that responded to their specific needs, with a high degree of customization and within shorter product life cycles. The adjective commonly used to describe approaches to product design and development was “customer-driven”, leading to a fundamentally customer-centric process (depicted in figure 20.2, right). Despite a few clear differences between the two scenarios, we still see many common elements, such as the focus on physical products; the existence of a distinct product life cycle in which products are first designed, then produced, and finally purchased and used; the fact that the customer is a relatively passive actor, whose major role is to buy goods and use them, eventually receiving some benefits in exchange. There is some customer involvement in the development process, through qualitative and quantitative market research, and thanks to a number of techniques such as Quality Function Deployment (Akao 2004). However, this involvement remains – as a matter of fact – promoted and managed by the firm. For instance, market research may lead to the definition of customer segments, or of “personas” representing user archetypes around which products can be designed (Grudin and Pruitt 2002). However, these are representative models developed by the firm, and not actual customers.

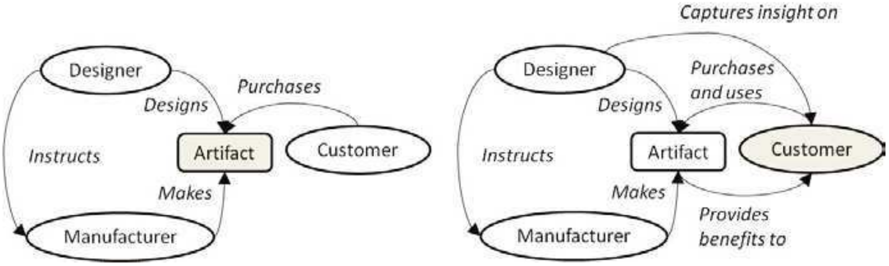

Fig. 20.2 The context of design within a Fordist (left) and post-Fordist (right) industrial environment

If one looks at industry today, it is possible to envisage a deeply changed scenario, which is likely to impact design activity in a powerful – and yet unexplored - way. It is possible to depict the elements that make up this changing scenario in figure 20.3. For clarity, the case of GOTO, a fictional provider of navigation systems and services will be used as an illustrative – though certainly not detailed – example in the following discussion.

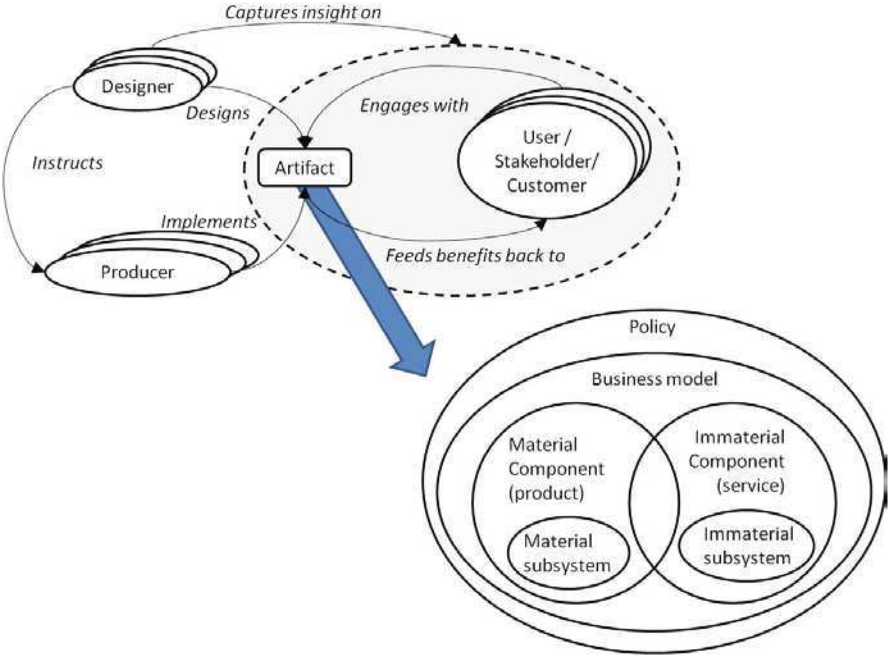

Fig. 20.3 The context of design within the emerging industrial environment

- First of all, the actors involved at the end of the chain are not simply customers but a mixture of customers (those who actually pay for a product or service they interact with, e.g. someone who buys a GOTO navigation system for his/her car), users (those who do not necessarily pay for the product or service, but do interact with it, e.g. people who use the maps on GOTO’s website and may add a comment on attractions such as restaurants and hotels) and stakeholders (who can provide or receive economic value from the product or service without actually *using* it, e.g. insurance companies who benefit from GOTO’s services because less congestion can lead to a decrease in accident claims). As a consequence, when specifying products, designers must interpet the traditional concept of “users” in a wider and more comprehensive way.
- The above mentioned actors do not simply *use* the artifact, but interact with it in a broader way, providing data (Magee 2008) or even creating innovative applications (von Hippel 2006). For instance, GOTO users may post their comments on restaurants and hotels, or post a trace of the trips they have made on their personal profile and feed it to a social network. In the near future, GOTO users may also feed the system with information on the real-time traffic they experience when traveling on minor roads that are not covered by fixed infrastructure. In this context, innovation is no longer a bridge between an active supplier designing something and a relatively passive customer adopting and using it, but a more complex phenomenon in which the line between the two becomes ever more blurred. In this new setting the user / customer / stakehold-

er not only receives value from the artifact but also generates it, and can in some instances also become a generator of innovation. So, figure 20.3 uses the somewhat more appropriate term “engages with” instead of “using” when describing interaction between users / customers / stakeholders and the system. When observing the system-in-use, those who design the artifact must therefore shift their attention from a relatively narrow concept of “usability” to a broader concept of “interaction-friendliness”.

- Not only the side of demand is different, but also the side of supply. Artifacts are no longer provided by linear supply chains made up of producers, assemblers and distributors, but by groupings of firms that operate in what authors have termed “value constellations” tied together by a business model (Normann and Ramirez 1993). This is probably a major disruption that characterizes modern business, since it tends to alter the traditional model whereby flows of goods and services run parallel and counter wise the flow of money, which used to lead to a clear and easily understandable balance between value (to the customer), cost (to the company) and profit (to the company). Conversely, it is nowadays fairly common to have businesses that provide goods and services without being directly paid by the party that receives them, and are nonetheless profitable since they are subsidized by different parties or by performing other activities. For instance, GOTO services may be enriched by valuable information without the end-users having to pay for it (e.g. GOTO devices can receive location-specific information over cellular networks, with advertisers paying for commercial reports on surrounding outlets. Or, real-time traffic data may be provided for free by highway operators). It follows that the cost-benefit analysis that is inherent to the design process must now follow increasingly complex routes that take the overall business model and intercompany tradeoffs into account, instead of a narrow and firm-specific perspective.
- The artifact itself also changes its nature. While designers were traditionally engaged with the design of physical products and devices, attention has progressively shifted to immaterial products and services (Morelli 2003, Tan and McAloone 2006). The current scenario shows a further step, with the blending of products and services into hybrid offerings (Panshef et al. 2009) that define a broader user experience. GOTO’s customers are not simply purchasing a navigation device, which would be useless without all of the services it enables. However, they are not only buying a service, since the material portion of the service is an integral part of the overall user experience. This high-level experience of a complex product-service becomes so dominant in customer choice, that elementary user requirements that would have been mandatory just a few years ago are now becoming secondary. For instance, if the overall experience granted to its users is compelling enough, GOTO might decide to sell navigation devices where users cannot perform simple tasks like replacing the batteries or upgrading the memory, thus reducing manufacturing cost and boosting revenues because of quicker product replacement cycles. The strong integration between product and service leads to new challenges in the design process both on the side of studying user experience, in translating it into requirements (Cas-

cini et al. 2010) and in solving technical tradeoffs in design and implementation.

- Both material and immaterial components of product-services are also highly systemic in nature, and their design therefore requires a strong integration effort with respect to the suprasystem to which they belong, and the subsystems they assemble (Lendaris 1986). For instance, GOTO devices must at the same time integrate themselves with enabling infrastructure (such as GPS and cellular systems) and must integrate components (such as commercially available or custom-designed chipsets and mapping information). As in all system design problems, choices related to the degree of modularity (Gershenson et al. 2003, Ishii and Yang 2003) become a key strategic issue, since designers must decide whether to take components and suprasystems as givens, thus leveraging on standards and economies of scale, or whether to “change the givens” and move towards integrated and proprietary architectures, in the attempt to optimize some technical feature or try to appropriate a greater amount of economic value. For instance, should GOTO try to introduce a “find your friends” feature to its offering, it should decide whether to build its own community, or partner with social networks that provide such services.
- Surrounding a given product-service system, one can easily recognize the existence of a business model that makes it profitable to the parties involved in the value constellation (Akkermans et al. 2004). And, above the business model, one recognizes that public policy can play a major role in making the business model viable or not. This is especially true if the technology has implications for society both in terms of potential externalities (just think of environmental friendliness of products, Abele et al. 2005), or because it could lead to abusive monopolistic settings and must therefore be kept in check. For instance, the GOTO offering may or not be profitable, depending on whether public actors decide to provide infrastructure (e.g. GPS, fixed infrastructure for traffic monitoring, etc.), whether they introduce incentives or penalties associated to road congestion and safe driving, and so on. In many instances, the technical design of the artifact is inextricably intertwined with both business models and public policy associated to the industry. While it is obvious that these issues cannot be tackled all at once, it is apparent that there must be ways to translate technical issues into business- and policy-related discussions, and vice-versa. Moreover, it is possible to envisage a further challenge, i.e. that of using technical concepts coming from the field of design also in the context of defining business models and policies.

The following table 20.1 tries to synthesize the above discussion in order to highlight the key challenges that designers operating in modern business have to tackle.

Table 20.1 A summary of challenges to design in the current scenario

Issue	As was	As is	Challenges to design activity
Customers	Customers buy and use products	Customers can be distinct from users and stakeholders, and can all act as providers of value and innovation	Moving from a perspective of "usability" to a broader concept of "interaction-friendliness" where users can provide value and innovation
Firms	Firms operate in linear supply chains	Firms operate in complex value constellations	Designing artifacts that will have to operate within complex business models. The flow of goods and services is not directly linked to the flow of money, making it difficult to compare costs (to the company), benefits (to the users) and economic reward.
Artifacts	Products or services	Integrated and systemic product-services linked in a high-level user experience	Understanding user experience, deploying requirements into product and service specifications, solving systemic tradeoffs between material and immaterial components, their supra- and sub-systems
Economic and social context	Relatively loose coupling between business models, public policies and products	Strong coupling between business models, public policy, and artifacts	Translating and deploying concepts between the level of technology, business and society. Supporting the design of business models and public policy.

20.4 Conclusions

In 1969, Herbert Simon raised prophesized the emergence of a "Science of the Artificial" as a single discipline bringing together efforts by professionals and organizations involved in "designing courses of action" across technical disciplines and industries. Forty years later, we are closer to fulfilling this vision. As the paper shows in its apparently disconnected sections 20.2 and 20.3, the *concept* of design as a science is indeed spreading in an increasing number of disciplines and - at the same time – the *context* of design is that of an increasingly interconnected world in which a clear-cut separation of design problems is becoming ever more difficult. This being true, design theory cannot rest on its laurels and simply celebrate its growing popularity, but must accept the challenge of providing guidance well beyond the technical fields where it originated, and proceed to the development of design support methods and tools that may be used in a broader context, such as product-service systems, business models and public policy.

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Chapter 21
Transferring Design Methods into Practice

K. Wallace[1]

Abstract Over the past 40 years there has been a rapid expansion of engineering design research. Researchers have proposed many methods to support designers, but there is evidence that many of these methods have not been transferred into practice. Why is this so? To address this question design practice, design research and knowledge transfer are discussed. Designers often consider new design methods to be complex, inflexible, incomplete, and not relevant to their working practices. The author's career spanned 40 years in design practice and design research. He reflects on the changes that have taken place and presents a case study of a successful transfer of a design method into practice. The main conclusion is that in too many cases it is nobody's job to transfer design methods into practice – there is a "missing link".

21.1 Introduction

Over many years Professor Herbert Birkhofer and his group have undertaken research into the nature of design methods and their use in industry. They conclude that the take up of methods is poor (Birkhofer et al 2002, Jänsch and Birkhofer 2007, Geis et al 2008). The reasons for this include:

- methods tend to be too complex, abstract and theoretical
- too much effort is needed to implement them
- the immediate benefit is not perceived
- methods do not fit the needs of designers and their working practices
- little or no training and support are provided by companies.

It is clear that useful design methods should be transferred from design research into practice, so it is important to ask who should responsible for this task.

By way of background, during my 40-year career in engineering design I have been extremely fortunate to have had almost continuous links with Rolls-Royce; to spend 30 years at the University of Cambridge with its long tradition of supporting engineering design; to work through a period of amazing changes in soci-

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ety and technology; to benefit from the increasing support for engineering design research from funding bodies such as the Engineering and Physical Sciences Research Council (EPSRC); and to have the opportunity to work with so many remarkable students and colleagues.

The number ‘7’ is often considered to be lucky and the years 1967, 1977, 1987, 1997 and 2007 have special significance for me. In 1967 I married my wife, graduated from university and started working for the Aero Engine Division of Rolls-Royce. In 1977 I was appointed Lecturer in Engineering Design at the University of Cambridge – the year that Pahl and Beitz published the first edition of their classic reference text on engineering design *Konstruktionslehre* (Pahl and Beitz 1977), which I was to go on to translate and edit (Pahl and Beitz 1984). In 1987, I started working on an EPSRC grant proposal that was eventually to result in the establishment of the Engineering Design Centre (EDC) at Cambridge in 1991. In 1997 I handed over the directorship of the EDC to Professor John Clarkson, and worked on a proposal to establish the University Technology Partnership (UTP) for Design. In 2007, I retired.

In the early 1960s, there was increasing concern about the UK’s declining share of international trade in engineering goodsp and the Feilden Report (Feilden 1963) prompted a growth of interest in engineering design. Around that time, many excellent texts on design methods were published and it is surprising that they are seldom referred to these days. Two had a particularly strong influence on me: Asimow’s book *Introduction to Design* (Asimow 1962); and the translation of Matousek’s book *Engineering Design* (Matousek 1963), which was edited by Professor D C Johnson at Cambridge.

There have been dramatic changes in society and technology. In the 1960s, products were “mechanical” in nature whereas now they tend to be “mechatronic”. When I started at Rolls-Royce, I worked on a drawing board and did my calculations using a slide rule. It was in the 1960s that Rolls-Royce took the very bold step of designing the first, and only, gas turbine with three shafts, the RB211. In the past 40 years this engine concept has been continually developed and has grown into the extremely successful Trent family of engines, which now power more than 50% of the world’s wide-body aircraft. Although the basic concept and working principles remain the same, the engines these days are more powerful, more reliable, more economical and, relatively, more environmentally friendly.

Products these days are much better and, in real terms, much cheaper than they were in the 1960s, so many companies and design teams are doing an excellent job – even if they are not using the new methods proposed by design researchers. The trends are clear: increasing globalisation; greater competition; shorter life cycles; increasing complexity of processes and products; large distributed design teams; reliance on IT; explosion in available knowledge[2]; and an urgent need for

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[2] There is a clear distinction between “knowledge” and “information”, but knowledge will be used here to include to both terms.

sustainable design. This all adds up to greatly increased pressures on companies and their design teams.

The fundamentals of engineering design have not changed in the past 40 years. They remain as set out in the books of the 1960s, though they are now often presented with increased levels of detail and using different terminology. Engineering design remains central to producing competitive products and, because of its current complexity, designers need all the support they can get. Ideally they should adopt the best design methods to emerge from design research. However, for this to happen a process of *knowledge transfer* has to take place between academic institutions and industrial companies, see figure 21.1

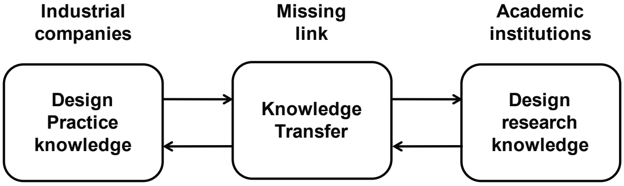

Fig. 21.1 Knowledge transfer – the missing link

21.2 Design Practice Knowledge

For an industrial company, the aim is to design and produce products that can be sold to generate income and make a profit. Design is a *knowledge processing activity* so designers rely on the knowledge available in the world, the specialist knowledge available within their companies, and their personal knowledge and experience, mostly stored in their heads. When creating new products, designers use and add to the *practice knowledge* about both their company's *design process* and its *products*. As practice knowledge is one of the greatest assets of companies, they attempt to keep it to themselves and protect it from their competitors.

One reason that designers are able to cope with the current complexity is that most products are not completely new, they follow a *development path*. Modern televisions, cars, washing machines and gas turbines are not *conceptually* different from those that were produced in the 1960s. Designers seldom start with a "blank sheet of paper". When, for example, next year's television is being designed, only certain aspects will be changed and improved – though these can pose considerable challenges. Significant step changes do take place, e.g. the change to flat screen televisions.

Designers clearly do use design methods, but often implicitly. If one is going to produce a complex modern product, such as a gas turbine, one has to be systematic, solve many problems, and define every detail of what is to be produced. All companies have their design methods. These are sometimes captured in procedure manuals, but frequently they are just part of the "shared understanding". Designers can cope because members of the team bring with them their experience of the development path which they acquired from working of previous company projects.

A design method is a prescriptive plan of action by which a class of design tasks can be tackled. For example, Brainstorming is a method to help generate ideas; and an Interaction Matrix is a method to search for connections between aspects of a problem. It is frequently stated, but often forgotten, that all methods should be adapted to the context and applied flexibly. Their purpose it to support the design process and they should not simply be undertaken as routine tasks. VDI 2221, for example, includes five full-page charts correlating design methods to stages of the design process (VDI 2221 1987).

Since the 1960s there has been rapid growth in the number of design methods published. Jones produced an early compilation (Jones 1970); and French, who was a Lecturer at Cambridge before becoming Professor of Engineering Design at Lancaster, revealed deep insights in his book *Engineering Design* (French 1971).

In the past 40 years an increasing number of undergraduate students have been taught design methods at universities and graduate students have helped to develop them as research projects. Many of these students have moved to posts in industry and taken their understanding of the methods with them. Some have risen to senior positions where they can influence the way the design processes in their companies are organised and there is some anecdotal evidence that this is beginning to have an impact. However, this effect is not reflected in the evidence gathered by Birkhofer's research group.

It can be argued that it should be the job of those working in industry actively to search out the best methods and transfer them into practice. However, the primary job of designers is to complete the current design task on time, leaving little time to seek out and implement new methods. One can only conclude that in many companies it is nobody's specific job to undertake this knowledge transfer.

21.3 Design Research Knowledge

For an academic institution, the aim is to carry out research projects to generate new knowledge that can be published widely in order to increase academic standing and generate research grant income. Like design, research is a *knowledge processing activity* so researchers rely on the knowledge available in the world, the specialist knowledge available within their group and their domain, and their personal knowledge and experience, mostly stored in their heads. When creating new knowledge, researchers use and add to *research knowledge* about both their group's *research process* and its *research topics*. As high-quality refereed publications are one of the greatest assets of academic institutions they, unlike companies, distribute their research knowledge as widely as possible.

The purpose of research is to understand the world we live in and develop insights, theories and models to explain the observed phenomena. We are familiar with the distinction between pure and applied research in the physical sciences. Reich in his thought-provoking editorial *My Method is Better!* (Reich 2010) draws a similar distinction between design research aimed at theoretical rigor and research aimed at improving design practice. As in the physical sciences, there is not a clear distinction between the two and they are not mutually exclusive. The focus of this discussion is on design research aimed at improving practice and this will frequently involve proposing improved design methods.

Design research leading to new methods is not new. An empirical study was undertaken by Marples at Cambridge in the late 1950s. He undertook two observational case studies that resulted in his classic paper *The Decisions of Engineering Design* in which he proposed the use of *Decision Trees* (Marples 1960). There were also early conferences in the UK devoted specifically to design methods: in London in 1962 (Jones and Thornley 1963); in Birmingham in 1965 (Gregory 1966); and in Portsmouth 1967 (Broadbent and Ward 1969). It is interesting to note that a large number of delegates from industry attended these conferences, and that some successful transfers of design methods into industry took place, for example the take up of PABLA (Problem Analysis by Logical Approach) by the UK's Atomic Weapons Research Establishment (PABLA 1966).

Design research is challenging for two main reasons. The first is that designing is a human activity and it is not possible to observe directly human mental actions; and the second is that the many factors influencing the design process are closely interrelated, so it is difficult to isolate an independent topic to study. The field has expanded rapidly but as yet there is no agreed design research methodology, taxonomy and terminology. This has led to the field becoming very fragmented. Evidence for this comes, for example, from analysing the key terms used in conference papers. In one such analysis, the key terms used in 390 papers were analysed and found to contain 1462 key terms, of these 1049 (72%) *were unique*.

To cope with the complexity, researchers often focus on their own specialised topics and ignore what is going on elsewhere. This generates "islands of research" with the work of other groups not referred to because it was "not invented here". Early work is seldom referenced and this leads to considerable "reinventing the wheel". This is not surprising considering the increasing pressures in the academic world to publish and meet assessment targets. Much design research is undertaken by young researchers with little or no experience of design practice, despite the growth of collaborative research projects with industrial partners. This has lead to a loss of "engineering" in design research, which can be seen in the lack of engineering examples and case studies in many current design publications.

There is another important issue that receives insufficient attention. Design methods are frequently embodied as software tools. Designers in industry spend a considerable amount of their working days on the computer using both dedicated design and analysis tools as well as the usual array of office tools. These software tools have been written by large teams of professional programmers and are powerful, robust and have sophisticated interfaces. It is not the main task of academic researchers to write software code, even if they are competent at it. They may need to code their proposed methods in order to test them, but the resulting software is not likely to be sophisticated, robust or user-friendly by modern standards. In addition, industrial companies have quality standards for the software they use. There is often a considerable gap between the prototype software tools produced by individual researchers and the standard of software that companies are prepared to install on their IT systems and practising designers are happy to use.

The issues discussed above were highlighted by Cantamessa who analysed papers from ICED conferences (Cantamessa 2001). For the 137 papers analysed, 42 (31%) made no reference to previous work; 47 (34%) had no industrial involvement; 63 (46%) were proposing new design methods; 38 (60%) described a new software tool; and 57 (90%) *ignored implementation issues*.

The above observations are probably not surprising. Young researchers are often either graduate students working on PhD projects with the objective of producing examinable theses or postdoctoral researchers working on short-term contracts with the objective building up a list of high-quality publications. We live in a competitive culture of permanent assessment, and little academic credit is given for transferring research results into industry.

There is clearly a need for consolidation in the design research field. One can argue that Pahl and Beitz's book was an early attempt to consolidate the field (Pahl and Beitz 1984) and that Hubka also made a significant contribution to consolidation through in his book *Principles of Engineering Design* (Hubka 1982).

There are some encouraging signs. For example, to consolidate the numerous design methods, (Geis and Birkhofer 2010) have proposed a logical and consistent way of classifying them into five groups. My personal interpretation of their classification is shown in figure 21.2.

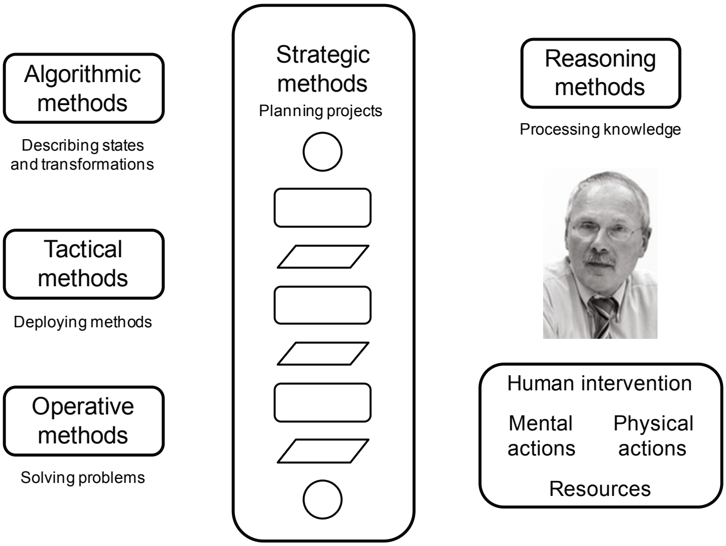

Fig. 21.2 Classification of design methods, after (Geis and Birkhofer 2010)

In a further attempt at consolidation, the issues of design research methodology, taxonomy and terminology have been addressed by (Blessing and Chakrabarti 2009). Another positive development is the Design Observatory approach being adopted by a group of academic institutions (Cash et al 2009).

As with designers, researchers too are under pressure and do not see knowledge transfer, which requires time, funding and special skills, as part of their jobs. This means that there are probably hundreds of prototype software tools, some of them potentially very useful, sitting on computer discs, forgotten and never used.

21.4 Knowledge Transfer – A Case Study

Since 1990, Rolls-Royce has established a network of 28 University Technology Centres (UTCs) to undertake their basic research. The UTCs are based in academic institutions and tackle a wide range of engineering disciplines such as combustion, aerodynamics and noise. The management of the UTC network is given high priority in the company and each individual project is assigned a Key Technology Customer who is responsible for ensuring that the research results are transferred into the company. Long-term collaborations with secure funding allow mutual understanding and trust to develop.

In 1998, Rolls-Royce established, in collaboration with BAE SYSTEMS, a UTC in Design. Because design is such a broad activity, the company realised that it could not be adequately covered by one academic institution, so it formed a University Technology Partnership (UTP) in Design between the Universities of Southampton (Product focus), Sheffield (People focus) and Cambridge (Knowledge focus). The overall aim of the UTP was to provide the companies with world-class research results to help them to improve their design processes.

The aim of the Knowledge research at Cambridge was to understand how to make more knowledge available to designers in a readily usable form and focused on understanding the *capture*, *storage* and *retrieval* of design knowledge. Many of the results that emerged directly and indirectly influenced the design process in Rolls-Royce, but one design method, called the Design Rationale editor (DRed), was very successfully transferred as a software tool. DRed was initially a research tool, but a stroke of luck meant that a senior design manager realised its wider potential and became its "Method Champion". In their paper (Geis et al 2008) state that an effective design method should:

- improve speed and effectiveness of communication
- help reaching agreement
- help plan, organise and control processes
- support individual time and project management
- be simple and flexible
- focus on results and be integrated into working practice

- take into account feedback from users.

With hindsight, it is interesting that DRed matches closely these recommendations. DRed is a simple, easy-to-use tool based on the Issue-Based Information System (IBIS) concept (Bracewell et al 2009). It supports the creation and capture of the rationale underpinning decisions. Essentially, DRed encourages clear and rigorous thinking; helps structure and clarify complex problems; aids communication with colleagues; supports discussions in meetings; and saves time and effort when preparing reports. DRed has passed all the required quality tests and is now available throughout Rolls-Royce through its PLM system. In some parts of the company, its use is mandatory for Design Reviews. It has been estimated that DRed is saving the company several million pounds a year and its contribution has been recognised by the award of several prizes.

In the conclusion to their paper (Geis et al 2008) state the following:

> ... successful method usage in industry can only be achieved when the whole procedure is set on four pillars: developing simple methods; adaption of the methods for the use and needs in companies; promotion of methods among future users; and last but not least, appropriate training in the use of methods.

The reasons for DRed's success include: (1) the long-term support given to its development through the UTP; (2) the dedication of a remarkable researcher, Rob Bracewell, who has outstanding research and software skills; (3) the nature of the tool itself, which is generic, adaptable, simple and robust; (4) the evolutionary way DRed was developed in direct collaboration with dedicated Key Technology Customers, David Knott and Michael Moss, and with designers at Rolls-Royce; (5) the support of a "Method Champion", Geoff Kirk, who was responsible for the design function throughout Rolls-Royce; and (6) the setting up of a DRed training programme by Jim Wickerson, who is responsible for design training.

Researching, developing and transferring methods take time. The basic research that led to DRed started in the UTP in 2002. The first version of the tool was uploaded onto the PLM system in 2005. It has undergone continuous development since then and a much enhanced version is just about to be released.

For DRed, the chances of successfully transferring it into industry were enhanced because there was a long-term research collaboration that led to a high level of mutual understanding and trust. Secure long-term funding through the UTP in Design meant that a senior researcher with rather special skills could dedicate himself to the project over many years. From the start, DRed was developed in close collaboration with a group of enthusiastic designers, who all provided continuous feedback that enabled rapid development cycles. By carefully selecting his software development platform and tools, Rob Bracewell was able to create a robust and user-friendly tool.

To be successful a design method has to be based on sound principles, be simple and intuitive to use, be flexible and robust, and provide an immediate benefit. Practising designers are under pressure and do not have the time to read through a 500-page manual! Knowledge transfer does not “just happen” it has to be planned, supported and worked at – and it takes a long time.

21.5 Conclusions

There is no doubt that the design research community has had an impact on design practice. Knowledge transfer has taken place through the growing numbers of students and researchers familiar with design methods who have taking up jobs in industry, and through the increasing number of collaborative projects with industry.

There is, however, considerable evidence, that many proposed methods are not transferred into practice. Part of the reason for this stems from the research community itself, which is undoubtedly fragmented. There is a need for consolidation along with agreement on a research methodology. There are encouraging signs.

Practising designers consider many design methods to be too complex, inflexible and fail to match their working practices – and many exist only as prototype software tools. Designers are under pressure to meet deadlines and do not see it as their jobs to seek out and implement new methods. Much design research is undertaken by young researchers who frequently have little or no experience of design practice and are only involved in design research for the duration of short-term projects. They too do not see it as their jobs to undertake knowledge transfer.

Professor Birkhofer’s research group argue that design methods will only be adopted when set on four pillars: simplicity, adaption, promotion and training. The DRed case study provides some evidence for the strength of this argument. It also shows that developing software tools and transferring them into industry requires considerable dedication, effort and, above all, time – so long-term collaborations with secure funding and senior management support are essential.

In the long term, there is a strong case for research funding bodies to set up special groups with the required skills and resources, e.g. commercial skills and dedicated programmers, to undertake the transformation of prototype software tools into robust tools that can easily be adopted by practising designers. In the short term, both researchers and practising designers should be given significant recognition for facilitating knowledge transfer.

The overriding problem is that knowledge transfer is frequently not seen as anybody’s job. There really needs to be an understanding right from the start of a research project as to how the knowledge transfer is to take place and who is to be responsible. The benefits from improving the transfer of useful methods into practice would be enormous.

Knowledge transfer is, without doubt, the “missing link”.

Acknowledgments Professor Herbert Birkhofer has made outstanding and unique contributions to design research and to promoting consolidation within the field. His leadership, inspiration and friendship are gratefully acknowledged.

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Chapter 22
Towards a Taxonomy of Design Research Areas

A. Chakrabarti[1]

Abstract This chapter focuses on the future of design research and the role of design lexicon research in shaping its future. We first discuss what we mean by “design”, “design research”, and by “future” of design research. We then discuss lexicon research in general, and our initial attempts at developing taxonomy of design research areas to help growth and sustenance of design research.

22.1 Introduction

This chapter is about the future of design research and the role of design lexicon research in shaping its future. We first discuss what we mean by “design”, “design research”, and by “future” of design research. We then discuss lexicon research in general, and our initial attempts at developing taxonomy to help growth and sustenance of design research.

22.2 Design and Design Research

There are many definitions of design. Some specify the way design is carried out, others the nature of the artefacts created as a result of design. Design research requires a definition that encompasses all kinds of design, and all phenomena associated with these. Here, we adapt the definition by Simon (Simon 1969), who defined design as a purposeful activity aimed at changing existing situations into preferred ones. The word design has two meanings: one as a verb and the other as a noun. The verb describes the act of designing, while the noun specifies the outcomes – the designs. We define design as a plan for intervention, that may include an artefact or artefacts, which when implemented, is meant to change an undesirable situation into a (less un-)desirable situation (Chakrabarti 2009). Designing is the process of identifying the undesirable and desirable situations, and developing designs. This definition encapsulates several essential, generic features of design.

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- Designs are *plans for intervention* that may include artefacts. Some definitions of design take designs only as artefacts, others take designs as plans for artefacts, but rarely as plans for action that may include artefacts. Not all designs include artefacts, and not all designs consist of only artefacts.
- The concepts of *undesirable and desirable situations* are essential to the act of designing. Without an undesirable situation, there is no designing. If all is well, there is no drive for designing – designing ceases to exist.
- It is the *implementation* of the design, and not the design itself that effects the desired change. An undesirable situation is not always an undesirable state of some system. Sometimes it is a state transition, and in general a set of set of states and their state transitions. For instance, the current state of the environment may not be undesirable, but its continual degradation.
- Designing involves identifying *both* these situations *and* developing the plan with which to change the undesirable into desirable. As Smithers (Smithers 1992) point out, designing involves both puzzle-making and puzzle-solving.

We now turn to design research. What is design research? Design research involves developing *design knowledge* – "knowledge of design and knowledge for design" (Horvath 2001), i.e. *descriptive* knowledge consisting of understanding the phenomena associated with design, and, based on this, *prescriptive* knowledge in the form of support, e.g. approaches, guidelines, methods and tools, for improving design practice (Blessing and Chakrabarti 2009). What are these phenomena associated with design – design phenomena? Adapted from Hales (Hales 1987), Blessing and Chakrabarti (Blessing and Chakrabarti 2009) speak of several facets that are inherent parts of the phenomena of design: people, products, processes, knowledge and tools, organisation, micro-economy and macro-economy. In this paper, we define phenomena associated with design – henceforth called design phenomena – as those that *govern the relationships between design and its facets*.

To understand design research better, let us contrast it with similar disciplines. Medicine as a discipline focuses strongly on practice, and is similar to design research in that it develops both descriptive theories and models of how organisms (particularly humans) and their health work; and prescriptive methods and tools to improve (or destroy) health of these organisms. Economics develops both descriptive theories and models of how an economy works, and prescriptive interventions to change or maintain economy in a preferred manner. Psychiatry develops descriptive theories and models of how human psyche works, and prescriptive interventions to change or maintain the psyche in preferred manners.

Similar to these disciplines, design research has both descriptive and prescriptive goals (Blessing and Chakrabarti 2009). As a whole its descriptive models and theories provide the basis on which prescriptive methods and tools are developed. While specific individuals or research groups may have more descriptive or prescriptive objectives, the discipline as a whole aims to develop knowledge with which to improve design. It, however, is distinctive from these other, similar disciplines in the sense that unlike in those disciplines, the focus in design research is on design phenomena. It is the design context that makes a research design research. Design research is therefore more specifically defined here as research that involves *developing knowledge of relationships between design and its facets* so as to better support design, i.e. designing and designs. For instance, creativity per se may not be an area of design research: depending on what aspects are researched, it may belong to psychology (individual creativity), sociology (social creativity), etc. However, design creativity is indeed an area of design research, since it explores the nature of creativity in designing, or the roles and influences of creativity on designing.

22.3 Future of Design Research

We now turn to the “future of design research”. “Future” of an entity refers to the sustainability and growth of the entity into the future. Our focus therefore is on sustainability (will it survive?) and growth (will it grow?) of design research. A research discipline has three kinds of activity: *research* activity in the discipline and the knowledge it produces, *teaching* and learning activity to disseminate or imbibe this knowledge, and *practice* activity utilising this knowledge. Future of design research, therefore, can be adjudged by the sustenance and growth of research about, and teaching and practice of design knowledge. Sustenance and growth of a discipline could therefore be measured in terms of these activities:

- Research (extent and quality of research activity): Funding for design research; no. of people working in design research; no. of conferences and journals in design research; no. of publications; quality of research outputs; career prospects for design researchers, e.g. promotions, prestige, etc.
- Teaching (extent and quality of teaching activity): No. of institutions teaching design knowledge; no. of people involved in teaching design knowledge; no. of courses offered; no. of students enrolling in design, quality of teaching outputs; career prospects for people involved in design teaching, etc.
- Practice (extent and quality of practice activity): No. of organizations utilizing design knowledge; no. of people trained in design knowledge working in industry; no. of design research outputs translated into practical tools; no. of organizations consulting on unitizing design knowledge in practice; quality of organizational outputs influenced by design knowledge; commercial impact of design knowledge in practice, e.g. no. of jobs created, revenue generated, etc.

If analysed using these measures, how does the future of design research look? Even though no systematic survey of trends has been carried out, results from industrial surveys at various points in time indicate an upward trend in the use of design methods. In 1999, a survey found that in an industry sector only 6 out of 16 applicable methods were used by at least 50% the respondent companies (Gouvinhas and Corbett 1999). In 2007, another survey in another sector showed an average of 50% respondents using 5 out of 8 applicable methods; 16 out of 19 of these respondents expected method-use to increase in the future (Mueller et al. 2007). Most organisations visited by Culley (Culley 2008) had a structured product development process. However, the general impression is that use of design methods in industry has grown far more slowly than expected.

Overall, it is hard to find reliable, direct statistics on industry penetration of design knowledge – via trained personnel or tools. However, using indirect measures, e.g. finding the number of people trained in design knowledge and assuming that they end up in industry, one could get an approximate idea. In India, for instance, the number of design teaching programmes grew steadily in the last ten years, from a mere few to about twenty, training about twenty times as many students to become design professionals (Chakrabarti 2007). The number of research programmes in design grew from none to five, training over a hundred students into various aspects of design research. In Indian Institute of Science, the number of Masters in Design students grew two and half time over the last decade, all being placed in well-paid design-related jobs in industry; the number of design research students grew from none to over 30 in the same decade, with 10 already graduated during this period. The number of national design councils grew from very few in the last millennium to a host of new councils, e.g. in Korea, China, Taiwan, and India.

What about research output? Since the first design methods workshop organised by Jones and Thornley in 1962 (Jones and Thornley 1963), there are now at least ten design-related conferences per year (ICED/Design, TMCE, DTM, CIE, Design Automation, ICoRD, AID/DCC, CIRP Design, IASDR, DRS, Design Education, MMEP, Design Matrix, Design Research Conference, etc.). The number of papers in the International Design Conference, Croatia grew steadily from 127 to 230 during 1998-2004 (Pavkovic et al. 2004). From only few design research journals in the 1970s, the number has grown to at least twenty (RED, JED, JMD, AIE, IJPD, etc). The number of laboratories for design research in the USA alone has grown from the three major design research labs (CMU, MIT and Stanford) during the 1980s to at least five times more (Oregon, Michigan, Georgia Tech, Texas A&M, Texas Austin, U of Michigan, MIT, CMU, Stanford, WPI, George Mason, Purdue, U of Illinois, etc). Overall, there has been an all-round growth of the discipline, even though it is hard to obtain exact data about how much this influenced industrial growth.

22.4 Academic Maturity of the Discipline and Consolidation

Many researchers complain that despite design research being around for over 50 years, and in spite of this tremendous growth, it is not clear how well the discipline has matured academically over these years. Three major issues with design research are highlighted (Blessing and Chakrabarti 2002): a lack of overview of existing research; a lack of use of results in practice; and a lack of scientific rigour. DRM (Blessing and Chakrabarti 2009, Blessing and Chakrabarti 2002) has been proposed as an attempt to help design research become more rigorous, and to provide a framework for placing existing pieces of research in a coherent manner using seven broad, design research types of (Blessing and Chakrabarti 2009), with the hope that research results with greater rigor and clearer usage context can be transformed easier into support for practice, and defended better the improvements they bring to practice. However, despite these and several attempts at developing ontologies of design and design knowledge, results from design research still seem hard to relate to one another.

Several authors speak of consolidation (Birkhofer 2006, Andreasen 2009) – bringing together and integrating the corpus of knowledge developed so far as outcomes of design research. This is important – to understand how the current research results relate to one another, and what the major achievements have been, so that progress can happen more systematically, making the most of earlier work to develop new knowledge.

Three kinds of consolidation come to mind:

- Consolidation of design phenomena: There is considerable debate as to what constitute design phenomena; consolidation should chart these out.
- Consolidation of areas of design research: Lack of this is indicated by the diversity and overlap of topics in design research conferences.
- Consolidation of terms and concepts to describe design research: Lack of this is indicated by the substantial variation in meaning in even the most commonly used concepts: e.g. function. Same terms are used to mean different concepts; similar concepts are expressed using different terms (Chakrabarti et al. 1995).

If done appropriately, consolidation should help in:

- Internal growth: There would be less duplication of work; greater and more effective communication among researchers; and faster and more systematic development of research based on appropriate, earlier work.
- External Recognition: There would be a recognisable body of work in the discipline, with milestones and key outcomes with greater scientific rigour and more widespread applications in practice.

However, consolidation cannot be carried out in a top-down manner; it must be done in a bottom-up fashion, much like how standards are developed in emergent areas voluntarily. We need a platform for research groups to voluntarily team up to take on the task of consolidation. Here are some broad suggestions:

- Develop a preliminary taxonomy of phenomena related to design.
- Develop a preliminary taxonomy of design research areas
- Develop a repository of design research papers, such as that suggested by Warren Seering in the Design Society AB meeting in 2003, and then to classify the se using the design research taxonomy.

- Develop a lexicon of terms and concepts used in the research papers within each research area. This can be initiated as a platform that allows various research groups to input their terms and concepts, and then form cross-group teams for them to develop taxonomy for each area; it should be possible to use these taxonomies together to consistently describe the work belonging to the overall discipline of design research.

22.5 Some Initial Proposals

Based on the definition of design phenomena proposed earlier, a preliminary taxonomy of design phenomena would consist of the following six broad categories (in addition to others that combine these categories): products; people; process; organisation, knowledge and tools; and economy.

In order to propose a taxonomy of design research areas or topics that offers a more coherent, and less divergent (Birkhofer 2006) set of areas, we could analyse the topics in design research conferences. Some of the topics in the International Conference on Research into Design (ICoRD'11) are: Design Theory and Research Methodology; Design for X; Design Creativity, Synthesis and Optimisation; Eco-Design and Sustainability; Aesthetics and Semantics; Human Factors in Design.

What is the basis of this list? Is there an inherent, underlying structure? Or are these but pragmatic compilations of areas of interest of people who attend these conferences? What is it that holds these topics together as representatives of a design research conference? The difficulty often faced at the time of submission of a paper in deciding the topic to which it fits, or that there are far too many topics to which it could fit, are possibly signs that the topics are not very well-structured. This also means that there will be many papers potentially of interest to an audience who would miss attending their presentations as a result of the papers being grouped under inappropriate themes or topics. A major repercussion of this is a reduction in visibility and citability of papers, weakening the essential mechanism using which scientific community develops knowledge in a staggered manner. What I would like to propose is to develop a taxonomy that is consistent on one hand with an agreed worldview of design research, and on the other allows mapping of the areas of interest that by praxis are included as design research topics.

Starting with the worldview of design research proposed in this chapter, the goal of design research is to develop design knowledge to support improvement of design. There are two underlying views: one is what we wish to improve – the *criteria*, and the other is the knowledge of design and its relationships to the facets – the *enablers*. Let us analyse the topics using these two views.

If we analyse "Design for X", "Design for Sustainability", "Eco-design", Design Aesthetics and Semantics", or "Design for emotions", we see criteria being the dominant view used. We want to design something to achieve X, sustainability, etc. On the other hand, “Design Optimisation”, “Design Synthesis” etc. refer to the various activities in designing; “Design Science”, “Design Theory and Methodology”, “Design Methods and Tools” refer to potential outcomes of design research. “Human factors in design” focuses on the relationship between people and design; “Design processes” on the relationship between design and its processes; “Applications in practice” on the relationship between design research outcomes and practice; “Design Management” on the relationship between design and organisation; and “Design collaboration” on the relationship between design and people – specifically their group/social aspects. “Design cognition” also focuses on the relationship between people and design, but the focus is on the cognitive rather than social aspects. “Computer aided conceptual design” focuses on computer tools for supporting conceptual design; the design stage is conceptual design, and the facet is the relationship between design and tools. “Automotive design synthesis” focuses on design synthesis in the context of automotives.

What we see is that there is possibly an underlying structure among these, something that is not carried out in a systematic manner through all topics. It seems that all papers focus on developing knowledge with which to understand or improve either design (i.e. research into design methodology) or design research (i.e. research into design research methodology). Therefore, taxonomy of design research areas should contain the characteristics of three aspects: design, design research, and design research methodology. This should ensure that one is able to categorise even those papers that focus on developing methodologies for research into developing methodologies for design with certain characteristics. For each of these, two major dimensions could be used: goals and enablers. These, together give six clusters: Design Goals, Design Enablers, Design research goals, Design research enablers, Design Research Methodology Research Goals, and Enablers:

- Design Goals: Goals of design under focus
  - Goals (time to market, market share, strength, manufacturability, cost, assembly, novelty, sustainability, aesthetics, ergonomics…)
  - Types (logos, computer programs, advertisements, buildings…)
  - Application areas (MEMS, Automotives, Aerospace, FMCG…)

- Design Enablers: Enablers of design under focus
  - Facets of design (people, product (aesthetic systems, symbolic systems, technical systems…), process, tools, organisation…)
  - Lifecycle Phases of the product (development, production, distribution, usage, after-use, all)
  - Stages of design (product planning, task clarification, conceptual design, embodiment, detailing, prototyping, testing…)
  - Activities of design (generate, simulate, evaluate, modify, select)
  - Outcomes (requirements, solutions)
  - Users of design (children, young, old, all…)

- Design Research Goals: Goals of the ontology, theory, models, methods or tools developed (e.g. increasing no. of concepts, modelling of cost, etc.)
- Design Research Enablers: Enablers of design research under focus
  - Stages of design research (Criteria, DS-I, PS, DS-II)
  - Outcomes of design research (theories, models, methods, tools…)
  - Technologies used (virtual reality, genetic programming …)
  - Users of design research (designers, assemblers, distributors…)

- Design Research (DR) Methodology Research Goals: Goals of design research, i.e. of the theory, model, method or tool to be developed for design research, under focus (e.g. rigour of findings, applicability in practice, etc.)
- Design Research Methodology Research Enablers: Enablers of design research methodology research under focus
  - Stages of DR methodology research (Criteria, DS-I, PS, DS-II)
  - Outcomes of design research methodology research (ontologies, theories, models, methods, tools…)
  - Technologies used (virtual reality, genetic programming …)
  - Users of design research methodology research (experienced design researchers, novice design researchers…)

The taxonomy is heavily inspired by the ACLODS (Kota and Chakrabarti 2010), DRM (Blessing and Chakrabarti 2009), and GEMS of SAPPhIRE framework (Srinivasan and Chakrabarti 2010). Note that a specific DR methodology research may be for a specific kind of design research, and a specific design research may focus on a specific kind of design. Therefore, the three sets have a set-subset relationship from deign research methodology to design research to design.

22.6 Application of the Taxonomy of Design Research Areas

We apply the taxonomy to classify various DR areas. “Design for assembly”, for instance, groups papers that have the design goal of (better) assembly, for the design lifecycle phase of production. Remaining fields of the taxonomy are unspecified: any research with the above design goal and phase fit into this area. A paper on “Design of an expert system for virtual assembly” can be classified as follows:

- Design Goals:
  - Design Goals (assembly)

- Design Enablers:
  - Lifecycle Phases of the product (production)

- Design Research Enablers:
  - Stages of design research (PS)
  - Outcomes of design research (tools)
  - Technologies used (expert system)

What this means is that the paper belongs to design research (and not DR methodology research, since all aspects of DR methodology research are empty), is focused on design for assembly, and more specifically on developing expert system tools for design for assembly. Clearly, the paper can be grouped within the area "Design for assembly", or into more specific areas, such as tools for design for assembly, expert system tools for design for assembly, etc. Another paper: "Observatory Research for Improving Design Observation" can be classified as:

- Design Enablers:
  - Lifecycle Phases of the product (production)

- Design Research Methodology Research Goals: (completeness and rigour of findings – in this case observations)
- Design Research Methodology Research Enablers:
  - Stages (PS)
  - Outcomes (Tools)
  - Users (design researchers involved in observational research)

Each aspect of the taxonomy can potentially have a hierarchy of elements. For instance, the "facets" are people, process, products, etc.; products can be technical, aesthetic, etc; economy can be micro- or macro-, etc. "Sustainability" has three components: economy, ecology and society; design for manufacture and assembly has two components: manufacture and assembly. In design for X, X can be manufacturability, cost, reliability, etc. Design for all, for instance, has only "users of design" specified – all. Typically, the topic "design processes', according to the DR taxonomy above, specifies only the process facet of design. Design Theory and Methodology, on the other hand, includes all outcomes of design research-theories, models, methods, tools etc. It is easy to see why the latter topic is a catch-all, and hence not very effective as a topic; all papers on "design processes" can be grouped also under this topic. The hierarchy within the taxonomy could be used to group papers together in a more consistent manner. For instance, let design goals have the following hierarchy: technical, ergonomic, user-experience and resource. Technical goals include strength, reliability, manufacturability, etc.; ergonomic goals include comfort and ease of use; user experience goals include aesthetic, semantic and emotional aspects; and resources include cost, life, environmental and sustainability. Using this, the topic "Design for cost" becomes more closely related to "Design for life" than say to "Design for usability".

How to identify topics for future conferences in design research? Taking inspiration from Lowe et al. (Lowe et al. 2001) who analysed keywords from papers in two conferences to develop a more compact set of keywords for use in ICED01, we suggest this. Potential authors to design research conferences could be asked to map their papers using the taxonomy. By comparing the maps, the papers could be grouped into clusters. Topics would emerge as a result of the strength of these clusters, and the number of clusters allowed in the conference (the no. of parallel sessions, no. of papers per session, etc). For a conference with a specific focus, the taxonomy should have appropriate aspects already filled out, e.g. in an eco-design conference, the design goal of all papers is pre-specified: environment-friendliness.

22.7 Summary and Initiations

Future of design research seems healthy in terms of its growth, although it is unclear how its results have impacted design practice. Long term sustenance of the discipline may depend on its academic maturity, which may require timely consolidation through voluntary inter-group collaborations. This chapter identifies the need for three kinds of consolidation, indicates possible means of achieving each, and provides a preliminary taxonomy for two of these. A group comprising Indian Institute of Science, TU Delft, Politecnico di Milano, Oregon State University and several others recently formed a team to work together to develop a design lexicon. All research groups are invited to join this effort.

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Chapter 23
Design Research and Education: A University Perspective

D. Marjanović[1]

Abstract Design, designing and design research become terms of their own, spread over disciplines, professional, cultural or social groups, geographic borders or borders of any kind. However the body of knowledge about design has evolved significantly and engineering design research is an increasingly mature stand alone discipline The article discuses the main activities of design departments at universities: design research, design practice and design education, supporting the view that none of the three can be viewed, discussed or practiced without the others. Design research, education and practice as performed in academia today are primarily a question of balance. Discussion is supported with selected examples. Indication of potential research areas is presented.

23.1 Introduction

Engineering design research has a long history of varied activities associated with it. However, the establishment of credible convincing and well supported new theories and innovative research approaches is an important and continuing task. Undertaking design research is intrinsically demanding for a number of reasons: evaluating models and methods by 'experiments' with industrial collaborators, generating large enough data sets, validating results in quite different design situations etc. From the early generation of design methods the body of knowledge about design has evolved significantly and engineering design research is an increasingly mature stand alone discipline.

Understanding terms like design and design research requires unified understanding upon notion and definitions of the terms being discussed. But design, designing and design research are terms of their own, spread over disciplines, professional, cultural or social groups, geographic borders or borders of any kind.

In this article we will discuss about design and design research based on experience and insight on research outcomes, discussions, understandings and misunderstandings during last two decades of WDK activity continued with the view

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through the lenses of the activities and attempts of The Design Society. Although we do not want to limit discourse on the "engineering design" since the background is inherited on the way the influence is unavoidable.

Hopefully this discussion article will enlighten doubts and dilemmas so often present within discussions about design research, design practice and design education. Merely we will try to advocate that none of the three could be viewed, discussed or practiced without the other two pillars of engineering. In addition we see design research, education and industrial cooperation as performed in academia today as question of balance, balance within the three mentioned issues: research, education and practice. It may be considered as a matter of compromise in space defined by constraints. Some practitioners may say the similar for design.

Although chapters of the same story, lifetime achievements of distinguished individuals or long term endeavours of institutes or departments research, design practice, and education are in constant tension. Research and design practice are based on elite processes while education is a mass process. Further, research and practice do not operate under same rules and consequently are hardly and randomly integrated. Practice is governed by values like simple design, easy of manufacturing, low cost, material properties, energy consumption and delivery timeframe, while research is concerned on why and how are those processes performed trying to improve those. For a quite of time both have been rewarding specialized knowledge and skill diminishing the impact of cultural and social influences. Very recently cultural differences, ECO design, ergonomics, and other traditionally „social contexts“ have become a design parameters and not more or less „irrelevant distractions“. This change of policy has resulted from a social shift that has resulted in parameterization of social values as market segments and probabilities that led to a financial terms and measurable values. Design research, practice and education coexist as a mutual drivers and will continue to do so in an uneasy tension challenging humans as before.

It is a common agreement that technology has influenced all aspects of human life. It did so in many ways. From the first toolmakers, craftsmen and artisans up to the nowadays designers, technology was developed and reshaped through a conscious efforts of many. At the same time the development was under constant tension: technology was and still is a driver and, at the same time, a constraint for a new development. In the huge segment of history design was randomly evolutive or evolutive by chance. We may think that once there was an intuitive creative method of born "designers" but the sum of all the efforts in design made us as we are today. From the early days technology and development have been shaped by conscious designing and we have been influenced by results.

Documentation of invention and development was essential. Documentation led to a structured development of early art and craft and as a consequence emergence of disciplines. Basic understanding and interpretation of reasoning and knowledge have been addressed through documented discipline and professional oriented views.

Between design disciplines that are primary concerned with “arrangements” of the components and engineering design there is endless variety of methods, tools, experimental research and experience gathered since time we have started to document the achievements.

The variety of design disciplines implies problems while thinking about design in general. It is hard to see what is common to the design disciplines, design procedures, design research and designing in practice.

23.2 Design Research at University

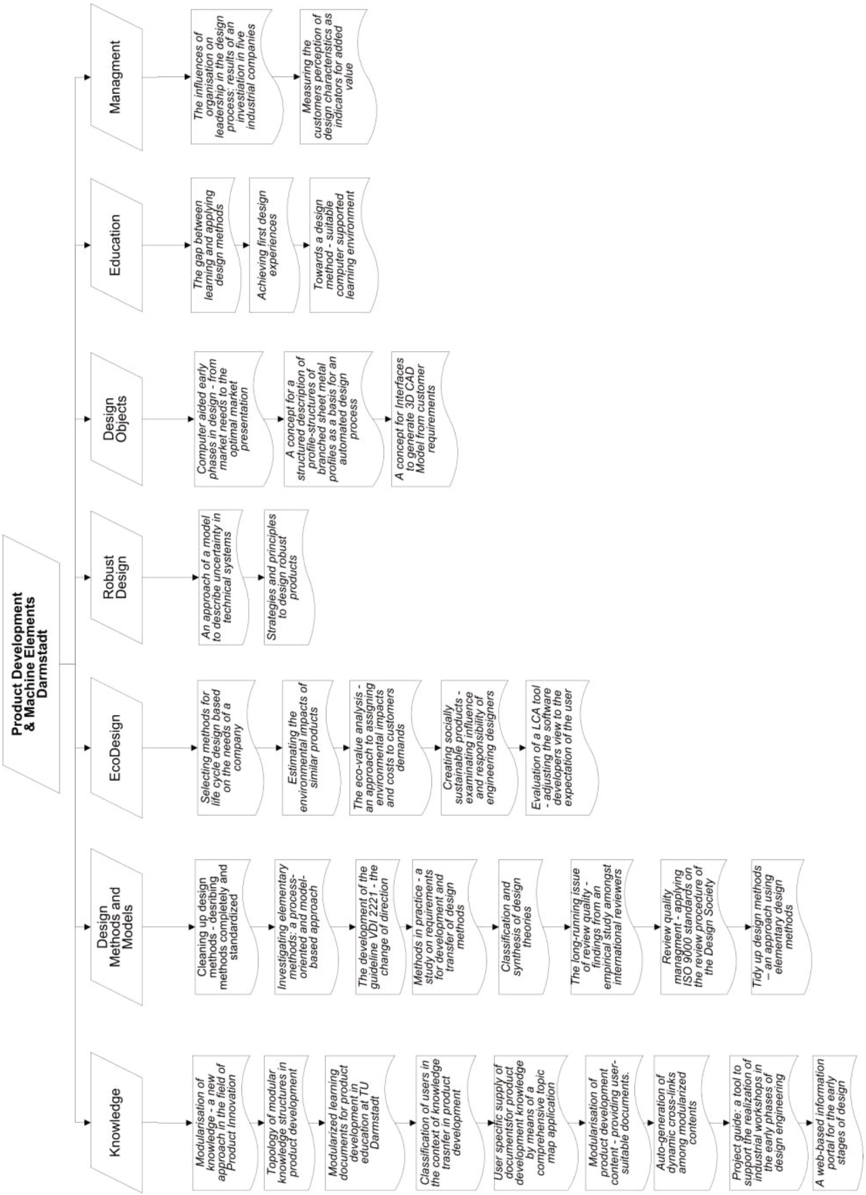
Generating knowledge about design and for design is the goal of discipline-oriented, scientific research of the design science community. This knowledge is the primary development force of the engineering design. Since the first works of Hansen, Roth and other pioneers of the field in the middle of the 20th century the theoretical research into engineering design has grown into a field of significant complexity. Therefore, it is not easy to see the trends of evolution, to identify the landmarks of development, to judge the scientific significance of various approaches, and to decide on the target fields for university research that will attract investors and rise the founding.

Orientation in the "jungle" of discipline-oriented research causes problems not only to new researchers but also to specialized experts due to high segmentation and multi disciplinary aspects of the matter. Additionally university research is, quite often synchronised and limited with PhD time scale.

Research at universities is therefore segmented in topics, depth and time. The management of research in university environment should take into account specifics that are not present in industrial environement. As illustrative example of such process we have used the results of researchers from Institute for Product development and Machine Elements at TU Darmstadt. The papers published at the DESIGN conferences in period 2000-2010 (figure 23.1) have been summarized and ordered in the following research chapters:

- Research about knowledge as a part of a PINNGATE project but extended afterwards incorporate research on knowledge structure, classification, caption, modularization, presentation and usage. (Birkhofer et al. 2002, Weiss et al. 2004, Birkhofer et al. 2004, Lenhart and Birkhofer 2006,Weber et al. 2008, Lenhart et al. 2008, Weiss and Birkhofer 2004, Weiss and Birkhofer 2006, Sauer et al. 2006)
- Design methods and tools topic included research of fundamental design process issues, classification of design theories and practical implementation of methods in industrial design practice. A special concern was given to quality of design research and review system. (Jänsch and Birkhofer 2006, Geis et al. 2008, Geis and Birkhofer 2010, Birkhofer et al. 2002, Zier et al. 2010, Birkhofer and Zhao 2010, Zhao and Birkhofer 2010, Birkhofer 2008)

- DfX - Design for X another regular heading of design conferences as a research chapter at PDM was represented in two sub disciplines: the ECO design and quite recently the Robust design. Although the number of papers under ECO design topic is relatively small the headings are well illustrations of the changes in research topics through time. (Ernzer and Birkhofer 2004, Dick et al. 2004, Oberender and Birkhofer 2004, Hanusch and Birkhofer 2010, Engelhardt et al. 2010, Mathias et al. 2010, Felsing et al. 2004)
- Research on Design objects is a result of industrial cooperation of PMD. This part of research may be viewed as implementation of research outcomes in practical engineering. (Birkhofer 2006, Gramlich et al. 2010, Chahadi et al. 2008)



F**ig. 23.1.** PMD research papers published at DESIGN conferences (Skec 2010)

- The lack of clear educational methods in engineering design have been answered with research of discrepancies in educational and practical usage of design methods and students' design experience gathered through international design contests. (Jänsch et al. 2006, Jänsch and Birkhofer 2004, Jänsch et al. 2004)

- The last research chapter in this overview entitled quite loosely as Management illustrates the broadness of research interests and activities at PMD. It is also a research motivated with the industrial need studying the leadership issues in design process. (Lüdcke and Birkhofer 2002, Oberender et al. 2004)

The time scale of research publications under above given chapters is illustrated in figure 23.2.

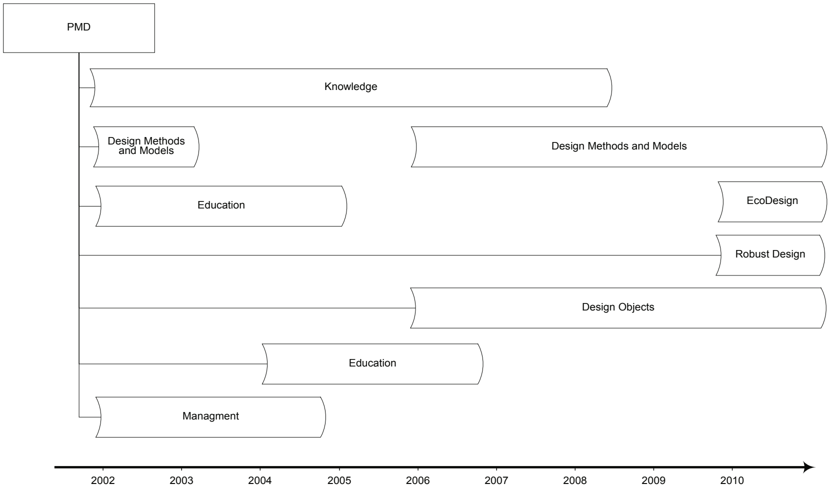


Fig. 23.2. PMD research topics in time as presented at DESIGN conference events (Skec 2010)

23.3 Teaching Engineering Design

In engineering design applied mathematics, physics and object (product) oriented matters dominate in the academic subjects. These facts are inseparable from engineering design but the essence of design requires much more. In "traditional" backbone engineering disciplines like Material science, Mechanics, Machine elements, Thermodynamics, etc. there is a common approach to content and methodology of learning with slight variations from school to school. In the design disciplines models and methods presented to the students of engineering design vary between universities, their institutes and design schools. The numerous models presented in the literature have not been presented within a holistic approach which combines all models or at least the dominating class of models existing. As a consequence (Geis et al. 2008) interactions and interfaces are not (or at least: rarely) defined between these models that were developed with specific intentions which justify their existence. These models portray design from different perspectives and focus on varying elements or actions in designing. As a common practice a selected prescriptive models are used in order to help students to develop an methodical approach to design process.

Information technology and tools have influenced, penetrated in and reshaped every aspect of our activities, the way we learn, act and even think. It also reshaped the education. Supporting tools like CAD have become a standard. The term CAD has lost significance once connected with, differentiating designing with computer based tools from the traditional drafting board design, since today there is virtually no design without CAD. Development of CAD tools was dominated by the needs of engineering designers. The highly replicated drafting procedures, analytical tools and planning procedures have been enriched with parametric, and feature based capabilities.

Although successfully implemented and used in almost every industrial and educational environment concerns regarding adaptability to design process needs, sustainability of documentation and lack of integration capabilities are still justified. Nevertheless supporting tools like CAD, PLM or FEA-systems will be even more important in future. Questions of integration, interfaces and usability have to be addressed. Knowledge management tools and protection of knowledge are further of high importance.

Additionally internet and e-learning tools made information instantly available thus changing the nature of students' literature and learning sources, communication methods between teachers and students having impact on the overall university organization. Availability of information and easiness of access to information is unfortunately to often misinterpret with acquired knowledge.

23.4 The Impact of Education Policy

The goals of engineering education have been formulated in many documents produced by universities, certified bodies and within education research reports. Without any claim to be complete the main goals of engineering educations could be formulated in a simple manner according to (Crawley et al. 2007). Competitive engineering students should:

- Acquire a solid knowledge of underlying sciences and technical fundamentals.
- Be competent to participate in development and operation of new products, processes, and systems.
- Be aware of the importance and strategic impact of research and technological development on society.

"Engineering design can not apply 'trial and error'" (Wallace 1952), neither can he afford a mistake. The same holds for education. Classical types of teaching, combination of lectures, exercises and individual or group project work still dominates in engineering design education. Project work an engineering adaptation of project based learning approaches traditionally serves as a link between education and practical engineering. In that sense it may be considered as an attempt to build experience that is so essential for future designer.

Unfortunately the current changes in high education implemented in most central European countries under pressure of urgent changes could raise the question if the policy makers of the educational systems have proposed a right policy, or the policy implementers have got a wrong message and implement the policy inappropriately.

The problem definition is of a crucial importance for the educational design process. The same holds for the policy change. A successful educational policy function will therefore enable a set of directives (i.e. inputs to the implementation function) that will resolve the discrepancy between the states "as is" and "to be". More precisely, the educational policy directives should establish the goals of the implementation function. A successful implementation function, oriented to the efficiency of the design process, could produce measurable and comparable effects. Inadequate policy or poor implementation will lead to undesirable results. Continuous failure in the implementation function will cause failure in the proposed policy process, regardless of the quality of the policy function. It is quite obvious that both aspects of educational policy react to the results they cause, revealing the presence and feedback. University professors gather feedback from industry, mostly through personal everyday routine contacts. It is quite common to hear that there is urgent need for engineering students to increase their personal and profession skills, independent thinking, teamwork and communication.

23.5 Industrial Needs as a Driver for Design Research

In everyday design and product development most of the efforts are given to incremental development and change in order to adapt products, manufacturing and business models to customers' requirements and to maintain stability and growth.

A day to day demand for high quality engineering is focused on details and a whole, regardless of product or system complexity incremental development relays on modifications in component design, material or manufacturing technology. Cooperation between university and industry under pragmatically set constraints is challenge for all. It is the responsibility of academia to be able to identify general research questions from particular case studies and everyday routine. As an example, the TRENIN, one of the current projects at the Chair of Design and Product Development in Zagreb will be used.

The engineering information has a central role in product development: it describes and documents the constitution and behaviour of the product; it drives the product development process and is the object of verification and validation procedures. The stakeholders (with different roles) in product development process need to leverage all relevant engineering information regardless of origin, format, and storage in order to help their organization to innovate, compete, provide service and grow. Reuse of engineering information including reasoning path, arguments, documentations, choices, critique and consequences is essential for maintaining the continuity of development process. Participants in the product development process need to be able to trace engineering information development.

The TRENIN project (www.trenin.org) is built on the state of the art developments in the exploration of principles for engineering information management. Further, the research explores how to incorporate development of the engineering information objects, sources, stakeholders, decisions and rationale into engineering information development space and extend in such way the state of the art methods and tools (figure 23.3). Merged Ontology for Engineering Design (MOED) (Ahmed and Storga 2009, Storga et al. 2008) extended with concepts gained from industrial practice, is used as a starting point for the formal description of the traceability records. The results of the former research justify approach to engineering information traceability that will be based on developed framework referring engineering information to the explanation of the context and audit trails in product development process.

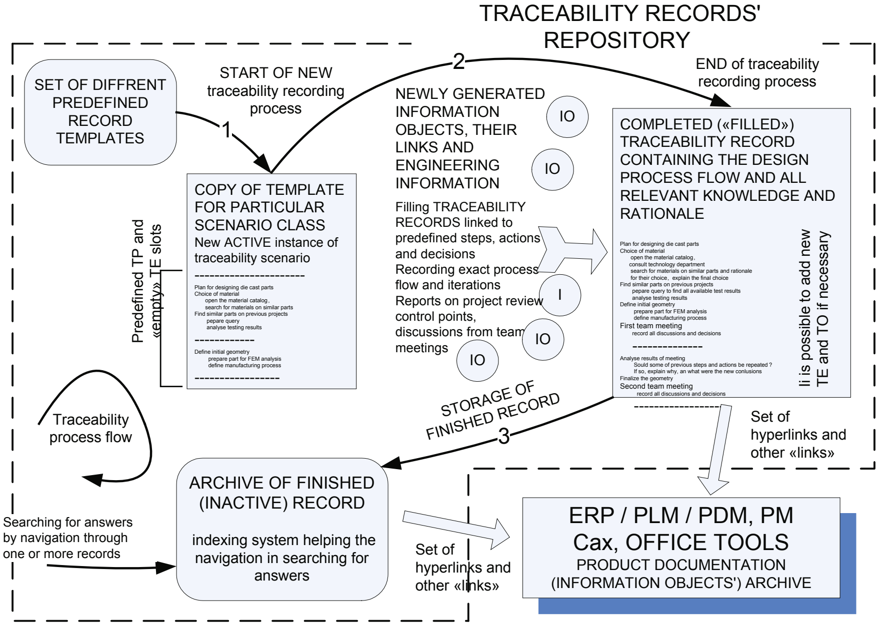


Fig. 23.3. Tracebility concept in TRENIN

Further research, will focus on the principles of the engineering information fragmentation among different information objects in order to support dynamic management and delivery of the engineering information based on the traceability principles.

23.6 The Future

The occasion of this paper requires a speculation about the further issues in engineering design research topics. It can be expected that further research will fall in two broad categories loosely defined as “formal” tools and methods and soft skills.

In the first category we can expect continuation of R&D based on formal tools and methods that will be used for analysis issues, handle complexity or for engineering change management. The support for early stages of design process, conceptualization, while the fuzziness in design process is at the peak, is also the potential space for further improvements. Expectations from early expert systems in the early phases have not been met. The first significant successes within the evolutionary design frameworks have been reported as optimisation systems. At the current stage the Computational Design Synthesis denote a set of algorithmic creation of designs implemented on computers involving an organized approach and methodological modelling (Cagan et al. 2005). It is a complex multidisciplinary research area that brings together advanced computational techniques and search algorithms with the knowledge about the object of design and design processes. Rather than just aiming at the optimisation, by building on the principles on which human designers arrive at a design solution the goal of the CDS can be formulated as to provide an assistance in situations where solving of a problem would require generation of a too large to cope number of variants (Stankovic 2011).

Informal methods that hardly can be formalised will require more attention. Complexity and interdisciplinarity present in design teams is proportional to design problems and requires high personal skills like communication, social interactions and trust. The balance within operational goals, creative needs, investment demands, creative ideas and future technology will mostly depend on team based judgment. Support for innovation. So far most of the innovation research efforts are concentrated on innovation of business processes. In many cases innovation is seen as an add-on, separate effort as opposed of it should be: integrated in all aspects of product development process through innovation policy and strategy. The expectations from the recently formed EU group of innovation practitioners initiated by EDC, KTH and TUM are quite high. The special quality of initiative arises from the fact that it is an joint effort of companies and academia. As mentioned above incremental development assures everyday bread and butter, but radical change is what makes technology breakthroughs. Current tools for raising the innovation potential, recognition and evaluation of innovation potentials, adjusting innovation proposals to technology and business are quite limited.

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Chapter 24

The Future of Design Research: Consolidation, Collaboration and Inter-Disciplinary Learning?

C. McMahon[1]

Abstract Multiple academic disciplines have researched in design in recent decades, and in so doing have developed a vibrant body of work exploring design from multiple perspectives. This is both a strength and a weakness. Diversity has led to a richness of insights, but at the expense of a lack of coherence and perhaps the perception of a fragmented community. It is proposed in this paper that it is thus timely for the communities that research in design and related areas to collaborate with a view to developing a consolidated understanding of the design research area. It is proposed that this may be achieved firstly by design researchers exploring where there is commonality and differences in results and approaches and secondly for the design community to explore where the work of other scholarly communities informs or challenges design research and vice versa. Examples of starting points for this work are proposed, together with suggestions for mechanisms to develop the collaboration.

24.1 Introduction

It is a great pleasure to be able to write on the future of design methods on the occasion of the retirement of Professor Herbert Birkhofer, one of the leading figures in engineering design methods of the past forty years. Professor Birkhofer has been part of a great movement in engineering design research that has established it as a vibrant and coherent body of work, with an active worldwide community that he has been especially instrumental in nurturing and developing. In this paper it will be argued that a solid foundation has thus been provided for the engineering design research community to join other research communities that have an interest in design and in product development and that have studied design-related topics from different perspectives in recent decades, to work towards a more coherent and unified view of design research.

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The reason for the different research perspectives in design is partly owing to a difference in research philosophy, but more fundamentally because of the different academic disciplines (mechanical engineering, manufacturing, art and design, architecture, management, etc.) that have pursued the research. A number of different viewpoints on design research and on design methodology have thus developed in parallel. It is proposed that a discussion is thus timely among the communities interested in design and in product development, to explore where there is agreement and commonality, where ideas can be shared, and where there are opportunities for design thinking to develop and to have more influence in our industries and wider societies.

The objective of this paper will be to present some initial ideas to provide a framework for this discussion of the design research space. In the paper it is proposed that two general approaches may be taken:

1. Identification of the key design research communities, then identification of where there is commonality in ideas and approaches between the communities, where there are differences and what the emerging ideas and challenges are seen to be.
2. Identification of other scholarly communities that study topics that are of relevance to and can inform design research, such as for example the technology management, philosophy of science and history of technology communities, and then exploring where those communities can offer insights that can inform or challenge design research and vice versa.

The paper will present preliminary ideas in these two areas from the perspective of a mechanical engineer and concentrating largely (but not exclusively) on issues in engineering design methodology. In particular, the paper will reflect on where the communities should accept and even celebrate differences in viewpoint, and on where ideas from outside mainstream design research may be particularly challenging to the design research community.

The structure of the paper is that first a very brief review will be given of the developments in design methodology research over the past forty years, and an overview given of the academic disciplines that carry out research that is relevant to design. Then the two approaches identified above will be introduced, with examples given of approaches that may be made in each regard.

24.2 Background

Research in design methods goes back many decades but it is in the last 30-40 years that it has really flourished. The early development in Germany of systematic approaches to engineering design is noted by Wallace and Blessing (Wallace and Blessing 2000), and there were significant related developments in neighbouring countries in Europe in the second half of the last century. Coming from rather different perspectives, a number of books on design methodology were published in the English language in the 1960s: the industrial designers Asimow and Archer published on design methods at this time, as well described by Cross (Cross 2007), and Herb Simon wrote in 1969 his "Sciences of the Artificial" from the perspective of a wide research base in economics, psychology, political science and sociology (Simon 1969). From these promising foundations the 1980s and 1990s were very active decades in design research: Hubka published in English in 1982 (Hubka 1982) and the English version of Pahl and Beitz was published in 1984 (Pahl and Beitz 1984). Crispin Hales seminal PhD thesis on the engineering design process in an industrial context was defended in 1987 (Hales 1987) and by that time the National Science Foundation (NSF) in the USA and the UK's Science and Engineering Research Council (SERC) had established programmes of research in design, and new journals were emerging (e.g. Research in Engineering Design and the Journal of Engineering Design). The years1988 to 1991 saw a real peak in activity with the establishment of the CIRP design seminar, the early days of the ASME Design Theory and Methodology (DTM) conference, and the ICED conference (see below) being held out of Europe for the first time.

There has been continuing progress in design research in the ensuing 20 years. From small beginnings in Rome in 1981 the International Conference on Engineering Design (ICED) has grown to attract regularly in the order of 500 participants, and to alternate between Europe and the rest of the world. Thirteen conferences were run under the auspices of Workshop Design Konstruction (WDK), who in 2001/3 handed the baton for the conferences to the Design Society. Professor Birkhofer was the first president of the Society and was highly instrumental in establishing it as a vibrant organisation. The Society has built up a portfolio of activities including the Engineering and Product Design Education (EPDE) and NordDesign conferences, and endorsement of the Dubrovnik 'Design' conferences, EDIProD, ICoRD and other events.

The growth in design research has accompanied a revolution in design practice, in particular through the pervasive use of information technology but also as companies have learned best practices from around the world. As well as systematic approaches to engineering design, a number of approaches have been developed to assist the designer with such learning, including techniques such as Quality Function Deployment (QFD) (ReVelle et al. 1998) and Design for Manufacture and Assembly (DFMA) (Boothroyd 1994). Equally revolutionary has been the ability to model products in 3D and then to physically realise these models through rapid manufacturing and prototyping techniques. Through the application of these and other methods there has been enormous progress in the quality, cost and performance of engineered artefacts.

Much of what has been described above is the result of work in the engineering design research communities, especially by mechanical and manufacturing engineers. They have not been alone in their work. The early work in design methods by industrial designers has been pursued by a vigorous community with an 'art and design' and industrial and product design perspective, and architects, interior and furniture designers are also very active. Technology and innovation management is particularly pursued by management researchers, as we shall see later, and design is of course of interest to urban planners (Hall 2002), students of the history of technology (Layton 1974), software engineers (Wasserman 1996) and information systems engineers (Hevner et al. 2004) to name but a few. Between these communities the range of insights into design and the work of the designer is enormous, but unfortunately the interactions between the communities are relatively limited: we are divided into 'academic silos', we attend different conferences, we submit to different journals and we work with different groups of colleagues (McMahon 2010). While these divisions are understandable for historic and geographical reasons, the problems that they lead to are of course that researchers may not be aware of important work in their fields, and also that from the perspective of those outside the community we may be seen as divided or our work may be poorly understood. The next section will begin to explore where there is agreement between the communities and where we need to explore and if possible resolve our differences.

24.3 Mapping the Design Research Space

In this section some examples of aspects of design will be presented in which there is both good and not so good agreement between the design research communities, concentrating on the engineering and industrial design disciplines. It is not intended in any way to be definitive, but rather to give examples of where there is merit in the research communities working together to map the design research space.

24.3.1 Are There Areas In Which We Can Agree?

As an example of an area in which there is apparent disagreement between design research disciplines, but on closer examination there is a substantial measure of agreement, let us look at models of the design process. There is an abundance in the literature: Pahl and Beitz, Eekels and Roozenburg, Pugh, Spiral, Ohsuga, Waterfall, BS7000, Vee-model and Stage-Gate, to name but a few. On the face of it, it might be thought that there is considerable diversity in these, but in fact most of the models have some or all of the following characteristics:

- Design progresses from the abstract to the concrete.
- A number of phases or stages may be identified, and these involve activities such as clarification of the task, expansion of concepts, refinement of concepts and documentation of the result.

- There is feedback and iteration in the processes.
- There are decision and evaluation points in the processes.
- The design task involves both the overall system and the components.
- The design process is part of a wider product introduction process, involving business and manufacturing issues.
- Aspects of the processes may be overlapped in order to achieve time reductions and effect improved communication.

In view of this agreement is it perhaps time for the design community to harmonise the various models into a unified process model, in the manner achieved by the software engineering community with the Unified Modelling Language (UML) (Fowler and Scott 2000)?

There are other areas in which there is a good measure of agreement in the different design communities, but differences in the language used. For example, Pahl and Beitz use the terms original, adaptive and variant to describe the degree of originality in the design context. Other terms for broadly the same issue include ‘conceptually static’ and ‘conceptually dynamic’ (Pugh 1991), and ‘routine, innovative and creative design’ (Gero 1990). This is another area that merits unification. The author’s experience with students and practising engineers over the years suggests that the issues are not so well understood and there is scope for clarification of the concepts and identification of good examples in each category (many engineers believe that they are doing original work when it is in fact adaptive). In addition, the relationship of adaptive design to the idea of dominant designs, which we will return to later, seems to be particularly important, as is understanding of the possibilities for creativity and innovation in the different design contexts.

There are also several areas in which a good deal of research has been done, and there seems to be the possibility of an agreed, coherent view, but it is not clear (at least to this author) that a clear and common understanding has yet emerged. An example of this is the representation and handing of risk and uncertainty in the design process. In this area the core techniques for representing risks are in place, and a number of simulation and approximation techniques have been developed (Goh et al. 2005). A number of methods for design teams to manage risks, and to collect and organise information about their understanding of risks, such as risk registers, FMEA, fault-tree analysis etc. have been developed, but some fundamental questions remain about how to handle uncertainty, on the role of fuzzy methods, and on the possibilities for assessing risk in early design phases. In an area such as this it is has been suggested in discussions in the Design Society that CIRP-style keynote papers should be produced to try to produce a consolidated view of the domain. Such an exercise would be even more valuable if representatives from across the design research communities were able to contribute. In addition to risk and uncertainty, the techniques to stimulate creativity and life cycle modelling are research topics where it is suggested that an informed consolidated view would be useful to the community, and computer-aided design also seems ripe for a review to see if the established commercial approaches that appear to be largely common across a wide range of engineering disciplines truly serve the needs of the designer (Smith 2007).

As a final example of an area in which it may be helpful to map the extent of agreement in the communities is that of 'Design-for-X' – the series of topics in which understanding is accumulated of how to design to maximise the performance of an artefact in some regard (manufacturability, reliability etc.). In this regard there are in the author's view two tasks for the wider design community. Firstly, to map those aspects of the space of the topics for which Design-for-X approaches have been produced, to identify gaps and to identify how complete is the knowledge in each area. Secondly, it should be explored whether a general approach to Design-for-X can be articulated. In this regard, current approaches seem to comprise:

1. Techniques for evaluation of the performance of the artefact with respect to category X, for example based on accumulated empirical knowledge (e.g. the Boothroyd's design-for-manufacture-and-assembly approach (Boothroyd 1994)) or on some other scientific principles.
2. Accumulated and organised knowledge that seeks to give advice in the form "if you wish to improve the performance of your artefact in respect of X, then consider doing the following".

Of course, the two approaches are inter-related: designs that perform poorly in evaluation (1) may be improved by applying knowledge from (2). The point here is that the design communities may present a generic Design-for-X approach as an example of a 'designerly way of thinking' (Cross 1982) which may be extended to other aspects such as social, economic and governmental systems.

24.3.2 Where Is There Less Agreement?

The nature of the design task and the degree of originality also seems to be an important factor in what is still a significant source of disagreement between the research communities – the importance of a systematic approach to the design activity. For some authors a systematic approach is key to improving the chance of a successful outcome (Panetta and Vigano 2008), while for others the very word 'method' is anathema (Childs 2010). An issue is the paucity of well-documented cases illustrating the merits of either point of view, but from the author's point of view design context is an important factor here: one can imagine that in designing a next-generation automobile or aircraft, or in designing a bespoke production machine, there are likely to be significant benefits from a systematic approach, while designing a new table lamp for aesthetic appeal is much less likely to so benefit. It is suggested therefore that the design communities should work to identify those design tasks likely to benefit most strongly from a systematic approach, and indicate the type of approach most appropriate to the task. They should, however, also recognize that:

- In many adaptive cases it may be appropriate to devote effort in directions that are not on the face of it design approaches - for example to develop a new material that allows a design constraint to be relieved, or a new analytical method that allows a design constraint boundary to be modelled more accurately (McMahon 1994).
- Many novel and inventive ideas can of course arise without the stimulus of any design method or training, and often do (but conversely those who have such ideas must often then develop the design and technical understanding to put them into practice, as was necessary for inventors like Alexander Graham Bell and Frank Whittle (Hughes 1987)).

It is when we start to explore the underlying paradigms in design research that there seems to be a greater opportunity for divergence of opinion. For example, Jude Chua Soo Meng (Meng 2009) describes an apparent rift between the influence of logical positivists with a strongly technical view of rationality and more open-ended constructivist approaches based on reflection and human experience. In (McMahon 2010) it is argued that any rift is not because we are pre-paradigmatic in a Kuhnian sense (with different researchers confronting the same phenomena and describing and interpreting them in different ways), but instead that design may be viewed as a field concerned with fundamental concepts which are contested and with observations and interpretations that have insight and utility. There are some parts of design research, towards the engineering science end of the spectrum (e.g. optimisation) where we are in a position to be paradigmatic, and others, towards the social sciences end of the spectrum, where it is not appropriate. It is our task as a research community to understand the nature of the spectrum and the possibility to agree on a paradigm where it is appropriate.

A final area in which there are many competing opinions and in which it is suggested that discussion between the design research communities would be very timely is in design theory, an area in which we have seen a recent flowering of activity (Hatchuel and Weil 2009, Shai et al. 2009). Here it is suggested that there is a role for groups such as the Design Society's Special Interest Group (SIG) in Design Theory to foster debate, not just between members of the Society but also with the wider research community.

24.3.3 Summary

The discussion above has proposed a number of different ways in which discussion between those with an interest in design research could be encouraged, and has provided example areas of focus for the discussion. These are summarized in Table 24.1.

Table 24.1: Topics for discussion and action by the design research communities

Action by the design research community	Example application area
Unify terminology	E.g. in describing degree of originality in a design task
Unify models	E.g. in design process models
Map the research space and identify agreed gaps	E.g. in risk and uncertainty or in Design-for-X
Identify and generalise the "designerly approach"	E.g. in Design-for-X or in problem solving
Understand where different approaches best apply	E.g. in systematic approaches
Understand differences between communities	E.g. in research paradigm

24.4 Learning from Other Communities

The previous section made suggestions for ways in which the various communities researching in design might work together to better understand the 'design research space'. It is suggested that there is much to be explored with researchers from disciplines not explicitly studying design – examples are given below from the domain of technology and information management, although much can be learned also from work psychology, the history of technology, the philosophy of science, to name but a few. These are necessarily very tentative suggestions, from a personal point of view, intended to stimulate debate in the community.

Technology and Innovation Management research is largely based in schools of management and of technology policy (Linton and Thongpapan 2004), and concerns itself with topics such as the development and introduction of new products, the management and organization of innovation, technology strategy, innovators and the evolution of technology and markets (Shane 2008) – on the face of it very similar interests to those of the of the design research community. It is a field in which practitioners debate the lack of a solid theoretical foundation and note the coexistence of radically different methods of approach and the absence of a precise and commonly accepted terminology (Nieto and Navas 2006). It is suggested that the design research community could contribute a great deal to this research, but equally that there are many respects in which the research challenges design researchers. Examples put forward for discussion include:

- The notion of 'dominant designs' (the basic architecture of a product or process that becomes the accepted market standard (Anderson and Tushman 1990)) is strong in the technology management community. To what extent is this compatible with the classification of original, adaptive and variant designs: are they essentially describing the same phenomenon, or if not is a unified approach possible? To what extent can a firm whose products adhere to the architecture of a 'dominant design' be informed by design methodology?

- The importance in the technology management literature of learning in technical communities. Hitt, Ireland and Lee propose that technological learning is linked to a firm's ability to develop, maintain and exploit dynamic core competencies, which are the foundation for competitive advantage (Hitt et al. 2000). For example Sahal proposes that engineers learn as they try to scale systems (make them larger, more powerful, smaller, more efficient, etc.) (Sahal 1981), and Vincenti (Vincenti 1990) discusses the work of the engineer in terms of the contribution of different communities to the design process. Are these ideas compatible with current research into design theory and methodology, and if not are there conflicts that need to be resolved? To what extent do the theoretical needs of the technology management community coincide with those of the design research community?

24.5 Conclusion

This paper has noted the diversity in design research, and in particular that while there has been a richness of insight there is a lack of coherence in the research community. It has been proposed that a collaborative effort to consolidate the design research domain is thus timely, and that the Design Society so ably led by Herbert Birkhofer can be at the forefront of this effort. It is proposed that this may be achieved firstly by design researchers exploring where there is commonality in ideas and approaches and where there are differences, and a number of ways of achieving this have been suggested. Secondly, the design community should explore where the work of other scholarly communities informs or challenges design research and vice versa.

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Chapter 25
Summary - General Reflections on Design Methodology

H. Birkhofer

The third group of authors does not directly phrase suggestions for optimisation, enhancement or replacement of Design Methodology. Instead, the focus is on how Design Methodology is developed and how it's further development should be carried out, looking at the surroundings in which product development operates and which requirements can be derived for further development.

25.1 Internal and external requirements for developing Design Methodology

In two contributions requirements are regarded in a kind of design-internal view concerning designers qualification and in a kind of design-external view concerning future economic systems.

In his contribution "What designers can learn from Leonardo, an ingenious artist, scientist and engineer" *Franke* examines the special features of Leonardo da Vinci and his activities as an artist, scientist and engineer. By reflecting on the special abilities of Leonardo, the skills necessary for developers in today's development context are derived. As an engineer, Leonardo was amazingly modern. He clarified the task consciously, worked out alternative proposals for solutions, often by referencing various disciplines and optimised solutions to achieve requirements and goals. A true increase in knowledge is only reached by precise observation of experiments. Franke emphasises the significance of experience for engineer-like thoughts and actions. A characteristic of engineering work in general and design work in particular is diligence in the development of solutions, ongoing analysis and overcoming of difficulties and the precise observation of natural phenomena. Leonardo was a master of sketching, which he understood as a presentation and documentation medium and as an extremely important medium for problem solving. However, this conscious visualisation and design of mental models is increasingly reduced by computer deployment, especially by modeling three-dimensional parts, components and products in CAD systems. In total, the contribution makes it clear that Leonardo was an extraordinary man and a protagonist of a modern engineer and designer, whose thinking and behaviour had remarkable similarities to current design activities.

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In his contribution “Design...but of what?” *Cantamessa* considers the current and future change in business models and user involvement in creating value in the dramatically changing situation of a global, increasingly interconnected world. Analyses of publications show that designing as an action is increasingly addressed by fields other than product development and that the classical picture of design as a solution of given design tasks within design departments becomes increasingly indistinct. Customer, user and stakeholders have different roles in the product, which does not necessarily mean that they all use the product, as shown by the case of mobile phone providers. The focus of design is extended beyond the actual product use to the goal of interaction friendliness, which helps everyone involved in the product reach their goals. Flows of goods and services are no longer linked to flows of money. Profitability studies instead follow increasingly complex paths that are formed in accordance with a superior business model and are aligned to intercompany tradeoffs. This trend is intensified by the change towards Product Service Systems (PSS). The demand for value, that a PSS system can cater to individual stakeholders, may even cause product changes that contrast with common requirements solely related to product usage. Such complex business models are much more dependent on public policies, which define or outline a superior usage framework. Both influence the design of PSS in a complex way, where common cost-benefit analyses from the perspective of manufacturers and customers are no longer sufficient. The concept for development methodology for PSS being considered for global business models is completely open at present.

25.2 The unsolved problem of Design Methodology transfer into practice

Unlike the creation, the transfer of methods and tools into design practice is rarely addressed in design research.

Wallace starts his contribution “Transferring design methods into practice” with a description of the dramatically increased requirements of design practice over the last few decades. He emphasises the central significance of design to the prosperity of companies and societal welfare. After this explanation of the relevance of design, he examines Design Methodology with its models, recommendations for procedure and methods that should reflect this importance but only meet the requirement due to its temporary nature and limitations in an insufficient way. Besides the deficiencies in content of the Design Methodology for practical use, he sees a substantial deficit in the inadequate transfer of design knowledge into practice. In the context of design practice, it is hugely important to use the right method at the right time. However, the task of selectively providing methods cannot be assigned to the individual designer. Unfortunately, design research barely addresses the task of method transfer and method implementation, which results in a serious transfer problem. Part of the problem is that young researchers without design experience often make method drafts and software is only realised as prototypes and therefore does not meet the requirements for industrial application. A specific example is given, illustrating how software, initially developed in research, can be implemented in a company successfully. The success of this implementation is, beside the quality of the software itself, a result of an evolutionary approach in further development, management accepting responsibility for implementation and usage, the motivation of a group of designers, and the trust and long-time cooperation between companies and research institutes.

25.3 The creation of Design Methodology by design research

Design Methodology is created by activities in design research. The awareness of different objectives of methodologies and research as well as the identification of "good" research is addressed by three authors.

Chakrabarti based his contribution "Towards a taxonomy of design research areas" on the deficits in the use of design knowledge in design practice in the broadest sense. His concern is with drawing up proposals for the improvement of design research for a research methodology aligned to economic criteria. He suggests structuring the field of research by taxonomies for design phenomena and design research areas to improve access to design knowledge by creating a repository of design research papers and to achieve consistent use of specialist terms by using a lexicon of terms. He distinguishes between the three activity areas design, design research and design research methodology, where goals and enablers are elaborated in every area. Initial examples show the suitability of this taxonomy for clearly structuring the research areas and their constitutive elements. The contribution also shows perspectives of this taxonomy that can be used for a clear and understandable naming of conference topics. Besides its scientific content the contribution also achieves real progress in the consolidation of design research and a deepened understanding of the research within the Design Methodology community.

Marjanović reflects, in his contribution "Design research and education: A university perspective*",* on the situation of design research and design education in universities concerning the requirements of design practice, and examines the differences between these areas. In the last 20 years of design research, a variety of knowledge, methods and tools has been created and it is nearly impossible to detect trends of evolution, landmarks of development and target fields. The management of research at universities follows its own laws, which are not necessarily in accordance with design practice. In design education, taught content varies considerably between universities and schools. In courses on methodical design, there is a lack of a common base and demonstration of interactions and interfaces. These are striking differences when compared to the field of CAX, which is much more focused on special CAD tools, knowledge management systems and e-learning tools. Distinct differences in the key areas also exist between design practice, which is dominated by incremental development, and design research, which favours radical innovations. Yet the author gives an example of how the field of incremental development can be supported by cooperation between universities and companies. Ontologies are used for the collection and utilisation of engineering information in the product development process to describe information and to structure the traceability of information. The future of engineering design research will be directed to two areas of action. The area of conceptualisation has to be supported by advanced computational techniques and capable search algorithms for knowledge. The field of communication and interaction in interdisciplinary teams needs new and improved informal methods to facilitate innovation of complex products in a globally distributed and interdisciplinary development environment.

McMahon, in his contribution “The future of design research: Consolidation, collaboration and inter-disciplinary learning?”, constructively considers the present appearance of Design Methodology and examines the variety and intensity of design research activities. The variety has strengths and weakness and expresses different research philosophies and views of the research object. After a historical overview of the origin of Design Methodology, two methods for his central approach to consolidation are presented, which consider research findings and research activities equally. His first proposal relates to the approach that mapping of the design research space is performed first of all. In doing so, it is apparent that different research approaches of key design research communities have a set of common characteristics concerning comprehension of the design procedure. Despite this, there is a need for action, especially concerning the comparison of process models, comparison of terminology, standardisation of naming of construction methods, control of risk and uncertainty (which is of central significance to design research), and harmonising and classification of different DFX approaches. There are strongly divergent opinions on the role and meaning of the systematic versus the creative approach, and on the question of which approach should be preferred when. Different expectations also exist in the scientific justification of Design Methodology by design theories, which established themselves as schools and emphasise differences rather than commonalities. A second claim of the contribution is the demand to also consider comparable work from other disciplines. Design Methodology is strongly interrelated with the fields of technology and innovation management. A mutual exchange of theories and methodologies could enrich both sides. The main concern of harmonising and consolidating the construction methodology is considered by the author as a particularly important task of the Design Society, which has already taken the first steps in this field.

25.4 Results and recognition

The six authors cover a vast range of topics and influences concerning the further development of Design Methodology (Figure 25.1).

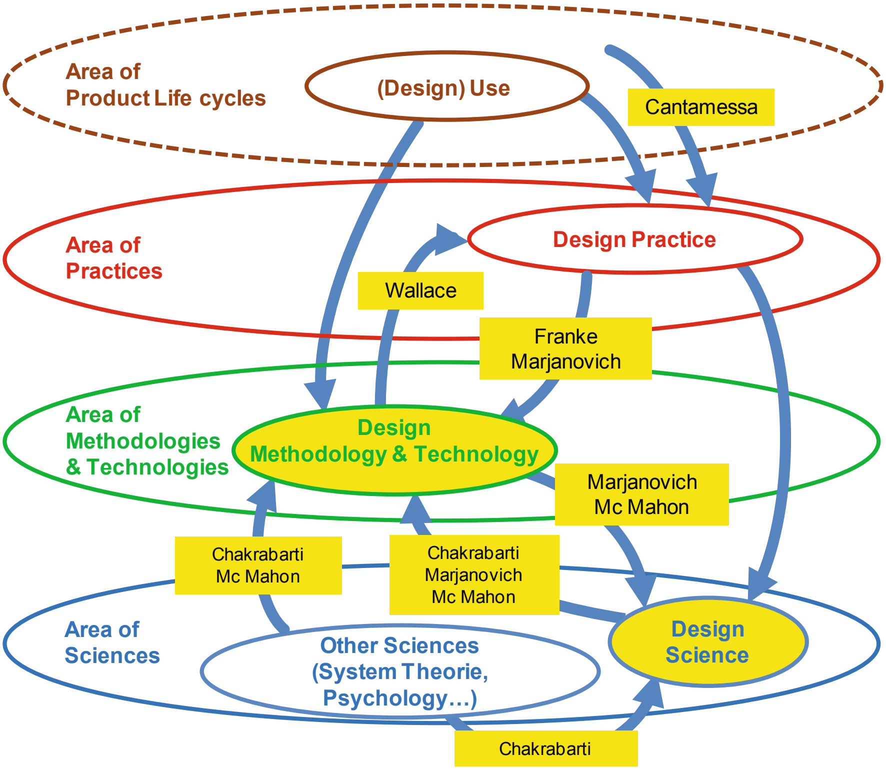

Fig. 25.1 Categorization of the contributions in the section “General reflections on Design Methodology” with regard to their research approach

The first two authors highlight the areas of designer qualifications and future economic systems from the multifaceted surrounding in which Design Methodology is effective or should be effective. No direct requirements of Design Methodology are outlined. Nevertheless, Design Methodology should take the specifications phrased in the two articles into consideration.

With his contribution that considers the almost entirely missing transfer of methodology elements from research to practice, *Wallace* enters “terra incognita”. He addresses a weak point in the process chain, from the development of design methodological suggestions up to their specific and permanent utilisation in design practice.

The last three authors critically examine the role of design research in developing efficient design methods. Deficits are named from the perspective of philosophy of science, demonstrated using academic education and compared to the role of CAX technologies. The last contribution, with its basic message of consolidating research results and knowledge, may be seen as a summary of most of the contributions previously mentioned

Chapter 26
Conclusions

H. Birkhofer

The 21 authors of this book cover a wide area of experiences and competences. Accordingly, opinions regarding the further development of Design Methodology are diverse. Nevertheless, key focal points can be recognised that are mentioned across multiple contributions. These focal points indicate important and urgent goals for change and innovation.

26.1 Further development towards a life cycle development methodology

The expansion of methodical work towards the entire life cycle, under holistic consideration of requirements and prerequisites, is unanimously considered to be indispensible. Designers have to think ahead through the life cycle to derive requirements and prerequisites to develop life cycle-adapted products. They need to cooperate with other company divisions to develop production, usage, recycling and disposal scenarios. If life cycle-oriented checklists for determining requirements are examined, this approach is already established in classical Design Methodology. Propositions for a comprehensive and practicable life cycle Design Methodology and a concept to integrate the variety of models, methods and tools from the specific life cycle phases are still missing. The new suggestions mentioned by the authors range from a more significant inclusion of Engineering Design to the integration of all DFX methodologies into a comprehensive life cycle methodology. Information technology provides life cycle management systems to control and document the flow of data and information. Nonetheless, the organisational, administrative and coordination tasks required for "real" life cycle development have been addressed reluctantly, for example, the selection and coordination of suppliers and internal labour for the optimum product architecture or the distinct definition of Product Service Systems under the consideration of all external stakeholders. These deficits are even more serious since life cycle development is already practiced in several companies, even if in a more pragmatic shape. In this case, the product manager usually supervises the entire life cycle of a product, from generation of the first idea to the release for series production. Design Methodology has a significant backlog, especially at this point.

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26.2 The further development to a holistic methodology for company development

A group of authors suggests not only focusing Design Methodology on the development of products but comprehensively on all company activities where “something new” is created. The formulation of business models and the development of technology are mentioned, which are both closely connected to Design Methodology. Such a holistic method for company development is especially necessary for customised products and product families varying in design (as increasingly demanded by global markets). The development of a comprehensive planning and Design Methodology is triggered by the complexity of current and future products and product creation processes. Products should create maximum value for stakeholders. This requires new business models, beneficial goods extended by services and purposeful modularisation of the services provided. Products are more frequently provided as a mix of products and services (PSS) in global alliances of providers (OEMs, suppliers, service providers), which increases the effort required for coordination drastically. As with complexity of products and processes, risk and uncertainty increase. This not only affects the benefit of a product but the totality of planning, products and service provision as well, which once more requires a holistic view of all company activities throughout the entire life cycle. To control complexity and uncertainty, powerful knowledge management, with partially or fully automated IT techniques (e.g. agent technology), is an essential core competence of a company. The variety of information that results from such a global, comprehensive and simultaneously differential provision of goods and services has to be manageable for the processing individual. This makes the use of visualisation tools increasingly important.

26.3 Definition of a human-centric Design Methodology

About a third of the contributions explicitly mention further development of Design Methodology for human adaption as a goal. Human thoughts and actions need to be accounted for, such as the high percentage of intuitive and creative processes, the widely unconscious and simultaneous execution of connections of problem and solution elements and the ability to associate and generate ideas based on mental models. The prescriptive work steps of methodical procedures should be extended in a way that the variety of individual styles of thinking and behaviour patterns are accounted for. Additionally, the creative development of, for example, fashionable and trend-oriented consumer goods should be supported better. To determine when the specific methodical prerequisites are supposed to be used (routine vs. non-routine actions), methods and metrics for the evaluation of the performance of a methodical procedure have to be developed. The distinctly prescriptive nature of the suggestions for Design Methodology for individual and problem-adapted control of development work has to be considered critically. The high percentage of learning processes in development work necessitates the supplementation and expansion of Design Methodology with individual work methods that controls the progress of the development based on actual findings. This extension of Design Methodology, from a methodology suited to explain structures, models and methods to an efficient and effective work methodology that meets the peculiarities of the problem-solving individual, could augment the acceptance of methodical work by advanced designers. To achieve this acceptance, the demand for a flexible use of Design Methodology and specific research on how to transfer research results into design practice need to be met. This “transfer research” has only just begun to develop.

26.4 The comprehensive integration of information technology into Design Methodology

An important subject is the conflict between extensive computer use in product development for 3D-modeling and the models and perceptions in Design Methodology. A couple of authors naturally use modern IT tools for knowledge management or simulation and integrate them into a methodical approach. Computers are used as work equipment to achieve ambitious goals in partially or fully automated information processing. To integrate computer use into the entire development process, one contribution chooses a rather pragmatic approach, where IT tools are used in every situation possible or helpful. This approach gains a methodical usability if considered as a “workbench”. It provides a comprehensive set of harmonised methods and tools that designers can choose from and use according to the specific context of the development step. Efficiency and effectiveness in product development can then be increased. The boldest vision of continuous integration of computer use into Design Methodology with a fusion of both approaches, including specific models and paradigms, is addressed in one contribution.

26.5 The consolidation of Design Methodology

Several authors addressed the last application area, which considers the scientific fundamentals on which the developed methods and technologies are based. Problems in design practice can be solved with methods and tools that have no scientific reasoning or theoretic proof. As a result, there is an unmanageable variety of methods and technologies, an abundance of different models and heterogeneous, poorly defined and therefore unclear or even incomprehensible terminology. Some authors demand a research methodology that is oriented on the rules of scientific work. This research methodology cannot be oriented on engineering research alone but requires other disciplines, such as economic research or psychology. Only in this way design science can account for being an action-based science. Another demand is for the harmonisation of models and terms, so that powerful, universally usable and broadly accepted methods and tools can be built on. However, the drive to harmonise can be too narrow, by only concentrating on the alignment and unification of terms. Since terms are always connected to concepts, ideas and models, harmonisation of terms has to start there. Measures to scientifically anchor Design Methodology in design science aim for consolidation. In recent years, this has particularly been addressed by the design community.

26.6 Closing remarks

The challenges of further development of Design Methodology are immense. In such a spacious, varied and dynamically developing knowledge area, this is to be expected. Over the last decades, a global and exceptionally agile design research community has developed that maintains a lively exchange of knowledge at various workshops and conferences and creates a huge number of publications and book contributions. It remains a steady hope that, even if only gradually, the problems addressed in this book can eventually be solved. However, it is clear that a final solution will never be achieved since the development of individuals, groups, companies and societies is never static. Irrespective of the size of the challenges, it should be every researcher’s incentive and pleasure to participate in finding solutions, ultimately contributing to the welfare of humanity.

Is further development of Design Methodology possible or is an entirely new methodology needed for product development? Forty years of design research and design practice, combined with the twenty-one contributions of this book, points to further development as the answer. Even though several authors raised the idea of a “new” Design Methodology, no argument has been made whose demands could not be fulfilled with an extension or adaption of today’s Design Methodology. Referring to the questions of chapter 1.1 in regard to the weaknesses of Design Methodology, the 21 contributions address burning issues of design practice as well as erroneous trends in past and current design research. The problem of an insufficient knowledge transfer from research to practice still is unsolved. And without any doubt the marketing of Design Methodology has to be improved by propagating and advertising Design Methodology to industry based on a professional marketing and business model. Research and sales are two completely different tasks and researchers rarely are good salesmen.

In considering the deficits and weaknesses, first we should be aware of the huge challenge, the enormous task and the comprehensive requirements research is tackling with the creation of a Design Methodology. Due to the variety of products, branches, companies and stakeholders and the multitude of disciplines contributing to such a holistic Methodology it's not to be expected to generate quick success. Secondly in considering the weaknesses of Design Methodology, the strengths and successes also need to be contemplated. The critical balancing of necessary changes, a focusing on the really important and pressing research activities and a forceful continuation of the enduring research endeavours should occur true to the motto:

The perfect is the enemy of the good.

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