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CHARACTERIZATION OF DESIGN SITUATIONS AND PROCESSES AND A PROCESS MODULE SET FOR PRODUCT DEVELOPMENT

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Abstract

Challenging boundary conditions, an increasing complexity of products and other factors demand for the support of product development processes by methods and tools. In order to shorten the duration of processes, to lower costs and to increase product quality, design engineers need systematic guidance for navigating unerringly through the design process.

In this contribution, a classification of design situations and design processes is presented. This classification builds the basis for a concept towards situational support of individual designers dealing with particular tasks and specific boundary conditions. Moreover, a set of general process modules is described, which was developed in order to allow for a systematic process analysis and process planning. Student design projects were analyzed with respect to process steps, input and output of processes, and method application, and a standardized form of process documentation was created. With the presented classification, the process module set and the stories extracted from the student project analysis, new possibilities for a situational access to relevant design knowledge arise.

1 Introduction

Design engineers in industry are subjected to a lot of requirements and boundary conditions influencing their daily work. These influences result from the complexity of products and processes, rapidly increasing internal and external demands for high quality products, time and cost reductions etc. Therefore, systematic guidance in the navigation through the design process is necessary. However, planning and controlling product development processes is much harder as for example business processes. This is especially the case in early phases where the problems are partially unclear, the knowledge on the solution space is still fuzzy and many decisions have to be made that have high impact on subsequent process phases.

Empirical observations in industry show that a significant percentage of decision processes in design exhibit patterns such as leaps and loops. These processes were typically highly iterative and ad-hoc planned, they led to poor results and should therefore be avoided [1]. A lack of efficient process planning in industry is also attested by case studies described by Eckert and Clarkson [2]. Here, a multitude of different plans was used by the participants within the observed organizations to conduct the course of a project, leading to an extremely high complexity of process planning. Of course, part of the problem can be found within organizational matters, which are not focus of this paper.

Part of the problem, however, can also be ascribed to the ill-structured and undetermined nature of design problems [3], which are the starting basis for design processes. Problem solving processes are naturally characterized by iterations, high variability and the need for creativity. Knowledge about constraints and boundary conditions changes with the ongoing process, decisions have to be made based on vague or non-available information etc. These are some of the differences compared to business processes, where the focus lies on making data and information available and controlling the information flow between various participants, standardizing and formalizing the activities, regardless of the actual contents [4].

All in all, the need for support of planning and controlling product development processes is evident. In design methodology, there exist several approaches towards this topic. Firstly, a large number of procedural models have been developed offering assistance in the navigation through the development process. Secondly, process modeling techniques and tools support the engineer in describing, visualizing and managing processes. These approaches will be discussed in more detail later in the paper. Moreover, in order to increase the efficiency of product development process and to obtain better results, the application of engineering design methods has shown great value.

The objectives of this contribution are to improve existing methods and techniques for process planning and controlling as well as to provide product developers with appropriate methods in each process step. In order to consider situational aspects, a characterization of design situations and design processes is developed. With respect to a target-oriented process support, a modular approach towards process descriptions is pursued. Generic process modules are defined which help to analyze, plan and control processes. Overall process networks can be configured from these process modules. In terms of giving the developer assistance in method application, an access to design methods by means of practical examples respectively use cases is proposed. These are derived in a standardized format from the analysis of student projects. In the following chapters, the proceeding in the course of the investigation is described, the results achieved so far are presented and discussed and finally, an outlook towards future work on the topic is given.

2 Analysis of Design Situations

In a literature research, design situations and processes were analyzed with respect to their characteristic features. The motivation for this step was the idea to support process planning and method application based on the specifics of the underlying design situation. Therefore, characteristics of design situations have to be known to be able to recommend appropriate process activities and methods.

Descriptions and classifications of design situations and activities have been developed before. Roozenburg and Cross [5] for example distinguish three dimensions of design activities: the dynamics of a design process, the designer and the design problem. Within the scope of this contribution, we focus on three elements that characterize the design situation:

- the design problem or task that requires corresponding design activities and processes to come to a solution,
- the designer or design team responsible for processing the tasks and
- the boundary conditions which influence the task processing by the designer.

2.1 Characteristics of Design Tasks and Problems

First, the characteristics of design tasks and problems are regarded. Here, the task novelty or level of innovation is an important feature. Pahl and Beitz [6] distinguish between original design, adaptive design and variant design. Within a design activity, all of these types of tasks might be found on different levels. An original design requires rather creative responses whereas variant design tasks can be typically processed with routine work.

The task complexity certainly has influences on the design process. The complexity of the task is typically connected to the complexity of the regarded technical system (especially if the task consists in developing a new concept for a particular system). Koller [7] describes ten complexity levels in technical systems starting with the simplest geometrical features such as needlepoints and ending with extremely complex technical systems such as processing plants, airplanes or ships. One of the first steps in the design process is of course to break down complexity into parts that can be handled. The classification of task complexity is rather arbitrary and has to fit the purpose. Here, we define four levels of complexity, according e.g. to the number of parts of the system (see table 1). Since the focus of the investigation lies on student projects, typical products include nutcrackers (low complexity), vacuum cleaners (medium complexity), bicycles (high complexity), and automobiles (very high complexity).

Dorst [3] develops a typology of design problems to enable a comprehensive study of the structure of design problems. The nature of design problems is described among other things with respect to structure (typically ill-structured) and determination of outcome (partly determined, partly underdetermined/uncertain, partly undetermined/free) which we include in our list. To deal with design problems, an interpretation is necessary which can be objective or subjective, depending on the situation. The problem solving process itself can be described partly as rational process, partly as reflection-in-action. These two explanations correspond to two opposed paradigms of design methodology.

A more precise and more complete differentiation of design problems is possible. The list could be extended and further characteristics identified, such as the type of specific knowledge that is required (mechanical, electronic, IT knowledge). For the purpose of this paper however, the mentioned aspects are sufficient.

2.2 Characteristics of Designers respectively Design Teams

For solving design problems, single designers or design teams are necessary. The team is defined by characteristics such as team size, team homogeneity, team communication abilities etc. The single designer is defined by his level of experience, which can be determined regarding two aspects: firstly, technical experience which refers to knowledge in the specific domain of the problem (automotive, process engineering etc.) and methodical experience (knowledge, skills etc.) which refers to the ability to solve problems regardless of the topic. Both types of experience are important. Dorst [8] describes seven distinct levels of design expertise from novice to visionary and places special importance on the development and transitions a designer undergoes from the low to the higher levels. The level of expertise will have influence on the way, a designer will handle a design problem, and therefore how the process and applied methods will look like. For our purpose, we include the levels novice, advanced beginner, competent, proficient and expert into our classification.

Further individual characteristics concerning e.g. personal style, inspiration and creativity, independence etc. will have an influence on the design process. For the same reasons as described above, we will restrict the investigation to the mentioned aspects. Just one more aspect is added to the list: the designer’s motivation for working on a particular design problem. Designers featuring internal initiative and personal attachment to the problem are likely to proceed differently than designers taking over a job they are instructed to deal with.

2.3 Characteristics of Boundary Conditions

Boundary conditions influence the designer’s work on the design problem to a significant degree. Here, following aspects are taken into consideration: the environment in which the problem is handled can typically be distinguished between industrial and academic. The type of environment has great impact on all the following boundary conditions. Technical limitations can refer for example to available hardware resources (computer, facilities for testing, prototyping etc.) and software resources (available software tools such as CAD, FEM etc.). Financial and time limitations exert more or less constraints on the design process and the search for solutions. Where a design project offers freedom of choice to the designer, there are usually less restrictions to the processes in order to come to a result. The individual freedom certainly depends on the type of problem and the phase of the project. It often goes hand in hand with the designer’s responsibility for the outcome and might therefore have influences on the designer’s behavior towards the task (dedication, motivation etc.). An aspect of major importance is the availability of relevant information.

2.4 Summary: Detailed Description of the Design Situation

In the previous passages, a number of criteria were mentioned which describe partial aspects of the design situation. In total, the specific values of each aspect characterize situations in their totality which themselves can also be classified. “Critical situations”, which always attract special interest in design methodology, can be differentiated from “normal situations”. They are typically characterized by extreme time pressure in combination for example with uncertain outcome, ill-defined structure of the problem, limited access to necessary resources etc. Table 1 gives an overview over the characteristics of design situations considered in this investigation.

Table 1. Characteristics of design situations

<table>
<tr><th colspan="2">Design task / problem</th><th colspan="3">Designer / Design Team</th><th colspan="2">Boundary Conditions</th></tr>
<tr><td rowspan="3">Task novelty, level of innovation</td><td>Original design</td><td rowspan="3">Team size</td><td colspan="2">Single Designer</td><td rowspan="2">Problem environment</td><td>Industrial</td></tr>
<tr><td>Adaptive design</td><td colspan="2">Team of 2-3 des.</td><td>Academic</td></tr>
<tr><td>Variant design</td><td colspan="2">Team of 4+ des.</td><td rowspan="2">Technical limitations</td><td>Restricted resources</td></tr>
<tr><td rowspan="4">Task (system) complexity, number of parts</td><td>Low (1-10 p.)</td><td rowspan="2">Team homogeneity</td><td colspan="2">Homogeneous</td><td>Resources available</td></tr>
<tr><td>Medium (10-20 p.)</td><td colspan="2">Heterogeneous</td><td rowspan="2">Time limitations</td><td>Time pressure</td></tr>
<tr><td>High (20-100 p.)</td><td rowspan="2">Motivation</td><td colspan="2">Internal motivation</td><td>No signif. restrictions</td></tr>
<tr><td>Very high (>100 p.)</td><td colspan="2">External motivation</td><td rowspan="2">Financial limitations</td><td>Financial pressure</td></tr>
<tr><td rowspan="3">Determination of outcome</td><td>Determined</td><td rowspan="4">Technical experience (knowledge, skills etc.)</td><td colspan="2">Novice</td><td>No signif. restrictions</td></tr>
<tr><td>Uncertain</td><td colspan="2">Advanced beginner</td><td rowspan="2">Freedom, responsibility</td><td>Low</td></tr>
<tr><td>Free</td><td colspan="2">Competent</td><td>High</td></tr>
<tr><td rowspan="3">Structure, clearness</td><td rowspan="2">Ill-defined, unstructured</td><td>Proficient</td><td>Expert</td><td rowspan="3">Information availability</td><td rowspan="2">Good access to information</td></tr>
<tr><td rowspan="4">Methodical experience (knowledge, skills etc.)</td><td colspan="2">Novice</td></tr>
<tr><td>Well-defined, structured</td><td colspan="2">Advanced beginner</td><td>Limited access to information</td></tr>
<tr><td rowspan="3">…</td><td rowspan="3">…</td><td colspan="2">Competent</td><td rowspan="3">…</td><td rowspan="3">…</td></tr>
<tr><td>Proficient</td><td>Expert</td></tr>
<tr><td>…</td><td colspan="2">…</td></tr>
</table>

3 Analysis of Design Processes

Depending on the specifics of the situation characteristics, the corresponding design processes will look differently. Here, a classification is also possible and has already been the topic of several publications (for instance in [1], [4]). The next passages describe a number of process characteristics which were identified within this investigation. An overview is given in table 2. Of course there are not only dependencies between characteristics of design situations and design processes, but also interrelations in between process characteristics.

The first type of characteristics deals with the origin of processes and the planning activities. The criterion “forward planning” refers to whether a process is planned short-, medium- or long-term in advance or rather ad-hoc (spontaneous processes). The criterion “process drivers” gives information on whether a process is driven by creativity and intuition or by rules and systematic behavior. The first case is an indication for ad-hoc planned, unstructured processes with undetermined outcome; the latter is the case for routine tasks.

The second type of characteristics in focus refers to planning certainty and possible standardization. Processes show a more or less distinct predictability, repeatability and variability. Processes which are suitable for standardization, re-use and therefore optimized planning are typically predictable, repeatable and invariable. In early phases of product development, this is rarely the case, which is also the reason that these processes are hard to plan and to control. Paetzold [4] characterizes processes in product development in order to determine whether current workflow management approaches could be applied for process optimization in this domain or not. The investigation shows that product development processes focus on problem solving, require a lot of creativity and demand for a certain degree of freedom in the designer’s activities. Workflow systems however require a defined structure of the processes to be modeled and support standardized, repeatable and invariable processes. The focus lies on improving data flows irrespective of the contents.

The level of detail (granularity) and the level of abstraction refer to how precisely processes are described. A process of high granularity includes detailed descriptions of all subprocesses. An example for an abstract, undetailed process is “search for alternative solutions”, a more concrete process is “search for available alternative solutions for a particular component in the company’s intranet”. The corresponding detailed process is e.g. “access the database”, “type in key words”, “screen the search results”, “open files” etc. A number of existing approaches refer to a general set of predefined process modules (for instance [9]), which are described in general terms on a rather low level of detail. Therefore, they are widely applicable and have to be specified for their concrete use in a particular situation. This paper follows a modular approach towards process descriptions, which is explained in the next chapter.

There are also certain characteristics which allow for an evaluation of processes. Badke-Schaub and Gehrlicher [1] distinguish five process patterns within their observations of decision making processes in industry. Leaps and loops are generally regarded as ineffective, leading to poor results, whereas cycles, sequences and meta-processes are more successful. The duration of processes is usually a matter of definition. When does a particular process start, where does it end? This mainly depends on the considered level of detail. The sum of all activities between two milestones can be defined as one process, which can then have a duration of several months. Also, a single brainstorming which takes place within a few hours can be called a process. And finally, the decision in the designer’s mind whether to pursue solution A or B, taking only a few seconds, is a process. The examples show that it is very important to comment on the regarded scale, when processes are discussed. At last, processes can be evaluated with respect to success, efficiency, quality of outcome etc. However, since it is not easy to measure these characteristics, this is an entire field of investigation of its own.

Table 2. Characteristics of design processes

Criteria	Specifics	Criteria	Specifics
Forward planning	Ad-hoc planning	Type of activities (problem solving dimension)	Goal planning
	Short-medium term planning		Goal analysis
	Long term planning		Goal structuring
Process driver, guideline	Intuition, creativity		Solution search
	Rules, systematics		Solution analysis
Predictability	Unpredictable		Solution evaluation
	Predictable		Decision
Repeatability	Non-repeatable		Goal control
	Repeatable	Process pattern	Leaps
Variability	Invariable (standardized)		Loops
	Variable (individual)		Cycles
Level of detail, granularity	High granularity		Sequences
	Low granularity		Meta-processes
Level of abstraction	Concrete, specific process	Duration	Short term (minutes, hours)
	Abstract, general processes		Medium term (days, weeks)
Design phase (concretization dimension)	Planning and clarifying the task		Long term (months, years)
	Conceptual design	Efficiency	Low efficiency
	Embodiment design		Medium efficiency
	Detail design		High efficiency

4 Development of a Process Module set for Product Development

The classification of design situations and design processes is prerequisite for a new methodical approach towards optimized process planning and control. The first concept was published and presented at the Symposium “Design for X” 2004 [10] and has been further developed since. The concept is based on a set of generic process modules which allow a systematic analysis and flexible configuration of process networks. As part of the concept, two aspects were dealt with: process contents and process modeling techniques.

4.1 Procedural Models, Contents and Dimensions of Processes

With respect to process contents, a large number of procedural models can be found in design methodology literature. Their purpose is to provide assistance in the navigation through the product development and design process. Different dimensions of process issues can be distinguished (see table 2). Different types of activities or process phases can be differentiated depending on the dimension in focus. Procedural models contain proposed effective sequences of these activities to be followed in order to obtain good results. These models often refer to one dimension in particular or show a mix of dimensions. The “problem solving” dimension focuses on process steps necessary to proceed from problem to solution For example the “search for alternative solutions” is usually one of the central process steps in these models. A representative model of this category is the Munich Procedural Model (MPM) developed by Lindemann [11], which is the basis for the set of process modules presented in this paper. The model is shown in figure 1. Other procedural models concentrate on the “product concretization” dimension and list process steps from abstract to concrete product representations. An example is the process plan described in guideline VDI 2221 [12]. The search for solutions is found here as well, but is specified with respect to the level of product concretization: e.g. on abstract functional, principle and concrete embodiment level.

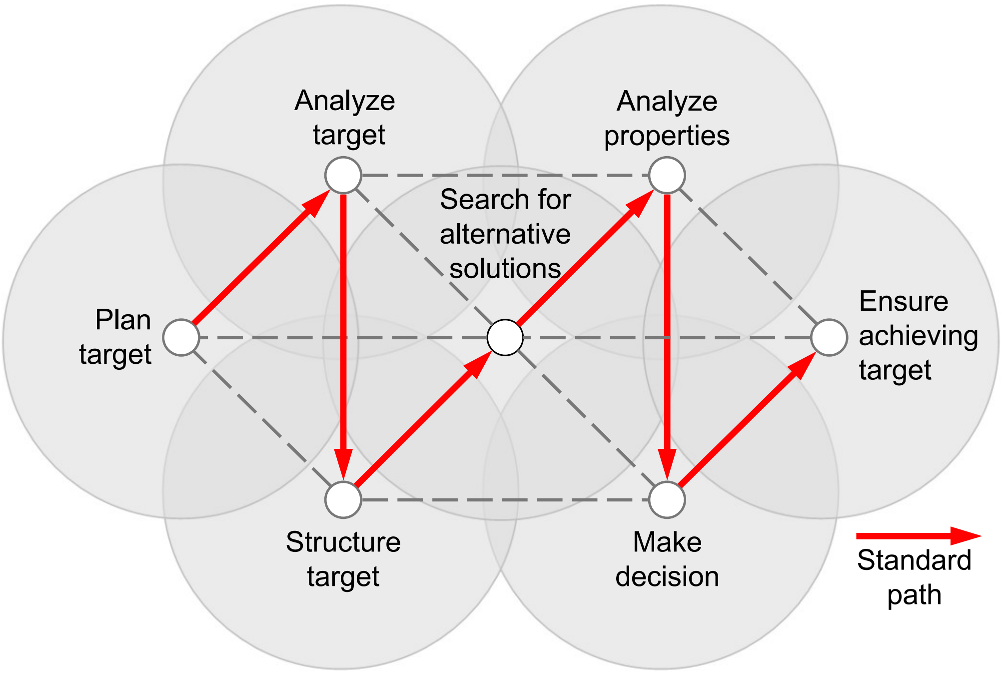

Figure 1. The Munich Prodedural Model (MPM)

4.2 Process Modeling, Process Description on detailed Levels

Procedural models describe processes on a superordinate level. They usually exhibit a linear sequence (from problem to solution, from requirements to detailed products) which does not correspond to how real processes are observed. In industrial practice, a lot of iterations take place, continuous jumps back and forth between levels of concretization etc.

Process modeling techniques serve for describing, visualizing and handling detailed processes on subordinate levels and are commonly implemented in software tools. Goh [13] gives an overview over existing process modeling techniques. Four modeling views can be distinguished, namely the functional, dynamic, object and task-based view. Examples for functional process modeling techniques are Data Flow Diagrams (DFD), methods of the IDEF family (e.g. IDEF0) and the Structured Analysis and Design Technique (SADT). Dynamic modeling is possible with Petri Nets, object modeling with the Unified Modeling Language (UML). Task-based process modeling is realized by means of Design Structure Matrices (DSM) as well as the Signposting approach developed in Cambridge [14].

The process modeling technique applied here is an adaptation of the process module approach described by Bichlmaier [9]. Developed based on SADT, a certain number of process modules were defined which can be selected from a database and combined to a network of processes to reproduce detailed process constellations. The possibility to reuse the same process modules in different positions of the whole process network offers potentials for improving the overall processes' efficiency. The configuration of the overall process in the sense of a process plan is made possible. The reaction to intermediary results, decisions and external influences on the process is done by adapting the process configuration and changing process modules. This approach, initially developed to support an integrated design and assembly planning, was adapted for our purposes and will be explained in more detail in the following.

4.3 Description of the Process Modules

The process module set represents a collection of generic product development processes. Components of these process modules are artifacts, activities, methods and tools. An exemplary process module is shown in figure 2.

<table>
<tr><td colspan="4">Process module: Describe problem on an abstract level (Structure target)</td></tr>
<tr><td>Input artifacts</td><td colspan="2">Activities</td><td>Output artifacts</td></tr>
<tr><td rowspan="3">• Detailed specification of problem or task
• Important requirements known
• Structured list of requirements
• Large amount of pieces of information
• Little knowledge on the structure and the core of the problem</td><td colspan="2">Reduction of large amounts of concrete information pieces to a small amount of relevant information; Removal of information that is not relevant for the target; Conversion of concrete detailed information to a higher and more abstract level; Increase in the comprehension of the system</td><td rowspan="3">• Information on a higher and more abstract level
• Increased comprehension of the system
• Relevant information extracted
• Structure of the problem known</td></tr>
<tr><td>Methods</td><td>Tools</td></tr>
<tr><td>• Text analysis
• Abstraction
• Black Box
• Function modeling
– Relation-oriented
– Exchange-oriented
– User-orientated</td><td>• Manual, description of proceeding and rules (doc)
• Template (ppt)
• Application example (doc)</td></tr>
</table>

Figure 2. Process module (example)

The term “artifact” is used here as a general concept for a wide range of items being object of product development processes. Artifacts are typically non-physical/virtual product models (conceptual sketches, CAD drawings etc.), physical product models (design model, functional prototype etc.), design documents (list of requirements, bill of materials etc.) etc. An artifact may serve as input for a process module, i.e. it is necessary for being able to carry out a certain process step. For example, a list of requirements is necessary in order to create adequate solutions to a design problem. An artifact may also be generated as result/output of a process module. The execution of the process step “create new solutions” typically delivers a significant amount of ideas in the form of hand-drawn sketches. Activities are distinguishable steps in the context of product development processes, where certain input artifacts are required to be able to carry out the activity and output artifacts are generated. Activities can be classified according to basic tasks such as divide, cluster, arrange or combine [15].

Single artifacts exhibit connections to other artifacts. Two different types of linkages are shown in figure 3. Firstly, artifacts can be linked within one particular process. Here, input artifacts show a causal connection to output artifacts; they are necessary for the output artifacts to be generated. Functional structures for example may be necessary for the generation of new alternative solutions, the knowledge of product properties may be a prerequisite for the selection of a final concept. Some processes contain the same artifact as input and output, if only the object itself is regarded. However the state of this artifact is changed during a design activity. Product requirements can be transformed from an unstructured collection of a multitude of requirements into a structured list of the most important requirements. Here, the input artifact “high number of unstructured requirements” is transformed into the output artifact “important requirements in structured form”. A second type of linkage between artifacts is found when regarding several different process modules. Artifacts represent the interfaces between two process modules. A functional structure, generated as output of one process step is utilized as input in a subsequent process step, for example the search for solutions to realize particular functions.

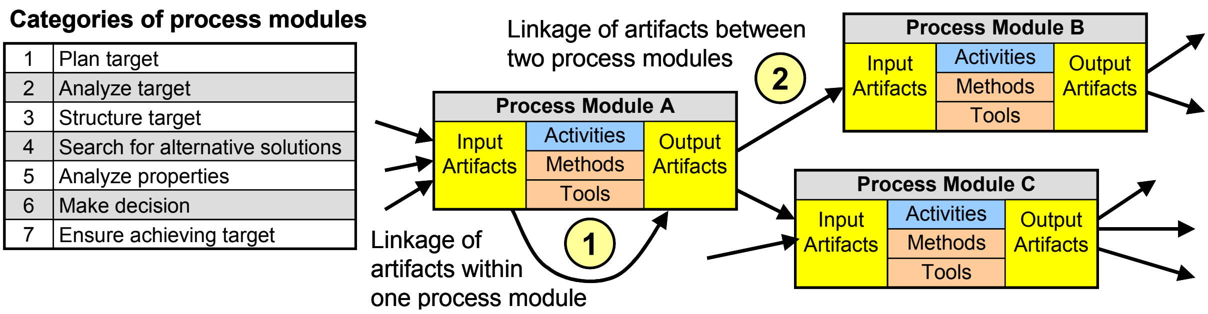

Figure 3. Linkage of artifacts within the network of process modules

Engineering design methods are applied to carry out design activities within a process module in order to transform input artifacts into output artifacts in an effective and efficient way. Methods are descriptions of systematic proceedings, characterized by rules or guidelines concerning their application and the depiction of correlations. Tools support the application of methods. Typical examples of tools are templates (forms, calculation tables etc.), checklists, software tools or information repositories (catalogs, databases etc.).

It has been stated before that design processes can be supported significantly by the application of working methods of product development. Therefore, in the developed concept, appropriate methods are assigned to specific process modules. However, the proposal of adequate methods and their detailed description do not suffice for their target-oriented and successful application. In most cases, there are several alternative methods available for implementation within the context of the same process. There is for instance a huge variety of methods which help determine a product's requirements: questionnaire, mindmapping, checklists, reverse engineering, cause-effects analysis, only to mention a few.

A lot of web-based computer systems offer method knowledge to users in academic and industrial environment (e.g. the CiDaD knowledge portal [16]). Moreover, the user-specific and situational selection, adaptation and application of methods are the subject of current scientific research. Corresponding approaches have been published for example by Braun and Lindemann [17]. Within the approach presented here, the access to relevant method knowledge in a specific situation is provided by practical examples or use cases. These are considered as an essential supplement besides abstract and general method descriptions that are already available in many sources. Thus, the comprehension of methods is facilitated, their application is increased and the user's individual needs in a specific design situation are better addressed. In addition, the access to relevant use cases is facilitated by comparison of the actual design situation to be supported with the design situation of the use cases. Here, the developed classification of design situations (see chapter 2) can be consulted.

4.4 Structure and Contents of the Process Module Set

The whole process module set in its current version contains 30 process modules. Each process module was assigned to one of seven categories (see figure 3). These categories correspond to the seven elements of the Munich Procedural Model. Lindemann [11] formulates task-oriented questions that are related to the elements of the MPM. For instance, the question "How can we describe the problem on an abstract level?" is related to the element in the MPM "Structure target". Thereby, the product developer is stimulated to reflect on his situation. As answer to the questions, certain methods and ways how to proceed are presented. The CiDaD knowledge portal [16] offers the possibility to access methods of product development by means of these task-oriented questions on the internet.

Table 3. Overview over process module set

1.1	Analyze the situation
1.2	Condense and structure the results of the analysis
1.3	Estimate future changes of individual characteristics
1.4	Generate alternative scenarios for future situations
1.5	Derive measures for product and process planning
2.1	Identify requirements
2.2	Identify correlations between requirements
2.3	Weight and structure requirements
2.4	Document requirements
3.1	Relate important requirements to product properties
3.2	Describe problem on an abstract level
3.3	Identify strengths and weaknesses
3.4	Identify degrees of freedom for the design and development
3.5	Formulate further target-oriented proceeding
4.1	Detect available solutions
4.2	Create new solutions
4.3	Extend existing solution spectrum with additional solutions
4.4	Structure and combine alternative solutions
5.1	Identify properties for analysis
5.2	Plan analysis of properties
5.3	Carry out analysis of properties
5.4	Evaluate results of the analysis of properties
6.1	Preselect adequate solutions
6.2	Prepare evaluation of alternative solutions
6.3	Carry out evaluation of alternative solutions
6.4	Interpret results of evaluation
6.5	Support the decision making
7.1	Identify possible critical target deviations and their causes
7.2	Evaluate risks
7.3	Reduce risks

The process modules are listed in table 3. They correspond to a high degree to the task-oriented questions formulated by Lindemann. Process module 3.2 “Describe problem on an abstract level” for instance corresponds to the question mentioned in the last paragraph.

The novelty within this approach is the explicit systematization of product development processes, which distinguishes and classifies processes on a more detailed level than procedures described by the MPM. The explicit enumeration of activities, artifacts, methods and tools, and the assignment to a limited number of process modules enables the next step: the development of strategies for process analysis and process synthesis based on the defined process module set. These strategies are introduced after briefly describing the case studies, which were consulted to evaluate the approach.

5 Description of Case Studies

Four student projects were consulted to develop and evaluate the utility of the new approach. In case study one, a student was given the task to develop innovative concepts for cracking walnuts. There were two focal points to the project. One was the generation of nutcracker solutions, the second was the application and evaluation of available methods of product development and conceptual design. The project served, so to speak, as playground for investigating the practicability of methods taught in academia. Therefore the product which was chosen, was relatively simple. In case study two, a student developed concepts for a derailer system suitable for recumbent bikes. Two different prototypes were built and tested on a test stand, which was conceptualized and realized in parallel to the development of the derailer system. Prior to the project, the student had been using recumbent bikes for a considerable time and had also been involved in activities dealing with the development of recumbent bikes. Since he had also attended some lectures and tutorials on engineering design methods, the level of technical as well as methodical experience can be regarded as rather high. In case study three, a student dedicated himself to the task of developing a folding bike suitable for tall persons. The motivation for this task was the fact that existing solutions on the market were not satisfying at all up to the present. The result of this project was the prototype of a folding bike showing an innovative folding mechanism. The student’s technical and methodical experience were similar to those of the student developing the derailer system. Case study four was still running at the time this paper was written. Here, two students in their second year at university were working on innovative concepts for a silent hairdryer. They had not gotten in touch with working methods of product development prior to the project. However, this lack in methodical experience was compensated very fast. A considerable part of the work at the start of the project consisted in acquiring method knowledge in order to proceed systematically. The documentation of former case studies (such as the other three projects mentioned) was provided.

In the following, some aspects are pointed out considering the different projects in comparison to each other. Here, the classification of design situations described in chapter 2 proves to be useful. An overview over the characteristics of each project's design situation according to the classification is given in table 4.

Table 4. Overview over case studies

Criteria defining design situation	Case study 1: nutcracker	Case study 2: bike derailer	Case study 3: folding bike	Case study 4: hairdryer
Task novelty, level of innovation	Original design, innovative solution principles desired	Original design, innovation desired (recumbent bikes)	Original design, new possibilities to fold a bicycle sought-after	Original design, innovation desired (silent hairdryer)
Task complexity (system complexity)	Low, 3-5 components	Medium, approx. 15 components	High, entire bicycle was considered	Medium, approx. 10 components
Determination of outcome	Uncertain, type of results (concept, prototype?) unclear	Determined, desired result = derailer for recumbent bikes	Free, no restrictions were set for the result	Uncertain, type of results (concept, prototype?) unclear
Structure, clearness of task	Well-defined, detailed description at the project start	Well-defined, detailed description at the project start	Well-defined, functio-nality of a bicycle well structured	Well-defined, detailed description at the project start
Team size	Single designer	Single designer	Single designer	Team of 2 students
Technical experience (knowledge, skills etc.)	Advanced beginner, product well-known; no involvement in development before	Proficient, longtime experience as user and developer of recumbent bicycles	Competent, 9th term academic knowledge special knowledge in bicycle technology	Advanced beginner, product well-known; no involvement in development before
Methodical experience (knowledge, skills etc.)	Advanced beginner, some method background at project start	Competent, lectures and tutorials on systematic product development	Competent: 1 thesis on systematic prod. development, several courses on methods	Novice, no contact with systematic product development before project
…	…	…	…	…

With respect to the novelty of the task, all projects are classified as original design, since a considerable level of innovation was sought-after in each case. Regarding task complexity, the folding bike represented the most complex task. The derailer system is only a subsystem of an entire bike and is therefore classified as medium complex. The hairdryer shows a comparable number of components as the derailer system. The smallest product complexity is displayed within the nutcracker. The most simple existing devices suitable for performing the task of cracking a nut consist of only one part (e.g. something similar to a stone). With respect to structure and clearness of the task, the statements given by the students were similar. The overall task was judged as well-structured and clear, since in most cases a rather detailed job description was given or worked out together with the supervisor of the project. The boundary conditions were similar, since all of the projects were realized in an academic environment. With respect to time limitations, the only restriction was to finish the project within 6 months, which is the regular duration for a semester thesis. Since the folding bike project covered an entire bike to be conceptualized, worked out in detail and be built as a prototype, this represented a significantly higher time pressure as in the other projects. The folding bike was also developed with a clear cost target and restricted budget, whereas the minimization of costs was not in focus in the other projects. Therefore, the folding bike project came closest to an industrial project, considering time and financial constraints.

6 Application Strategies for the Process Modules

Two strategies were developed for applying the concept of the process module set in product development projects. First, strategies for the analysis of completed processes were devised. The purpose is the transfer of relevant knowledge (adequate process sequences, successful method application) to new situations. In addition, strategies for process synthesis in the sense of process planning and controlling were developed. Here, mechanisms for the configuration of process networks are discussed.

6.1 Process Analysis

The four case studies were subjected to a process analysis. For this purpose, a brief standardized documentation of the particular process steps within the projects was generated in table form. This document was generated based on the student's semester thesis, which contains information on the project in a more detailed form (motivation, proceeding, applied methods, results, reflection etc.). The idea of the standardized process table is to obtain a quick overview over relevant project specific information, which gives more details than the table of content and is more appropriate for a quick access than browsing through the entire semester thesis often containing 100 and more pages. Table 5 shows an excerpt from the process table of the nutcracker case study.

Table 5. Process table of the nutcracker project (excerpt)

Nr	Process step	Input artifacts	Output artifacts	Methods	Tools
1	Identification and collection of existing nutcracker solutions	• Given task to develop innovative nutcracker concepts	• Collection of available nutcracker variants • Collection of patents dealing with the topic nutcracker	• Investigation	• Internet search engines and auction sites (Google, Yahoo, Ebay) • Patent databases
2	Analysis, clustering and structuring solutions which were found in process step 1	• Collection of nutcracker variants available on the market • Collection of patents dealing with the topic nutcracker	• 3 basic types of manu-ally operated nutcrackers (lever, wedge, impact) • 4 especially innovative nutcracker concepts identified	• Analysis by means of physical effects • Strength/weakness analysis	• Catalog of physical effects
3	Derivation of potential for optimization	• Collection of nutcracker variants and patents • 3 basic types of manu-ally operated nutcrackers • 4 innovative nutcracker concepts	• Weak spots of conventional nutcracker solutions identified • Need for product development process derived	• Functional analysis	• Relation-oriented functional modeling • Problem formulations

The next step in the process analysis was the comparison of these specific processes, taken from real projects, with the general process modules from the process module set. The application of this procedure to all documented process steps from the four case studies, lead to the following observations (among others):

- Sometimes one concrete process step matched exactly one process module. In other cases one real process step covered two or more process modules. An example of such a process comparison is shown in figure 4. Sometimes it was not possible to find a process module suitable to describe the real process step. This indicates that the process module set yet has to be extended to be able to describe real product development processes more properly.

- When looking at one particular project, it is possible to identifiy certain process patterns in the sense of sequences of process modules. The example of the derailer system project demonstrates that throughout the project the standard path of the MPM (see figure 1) has been followed. A recursion is observed where the test stand was developed. Figure 5 shows the process pattern of the derailer system project on a superordinate level.

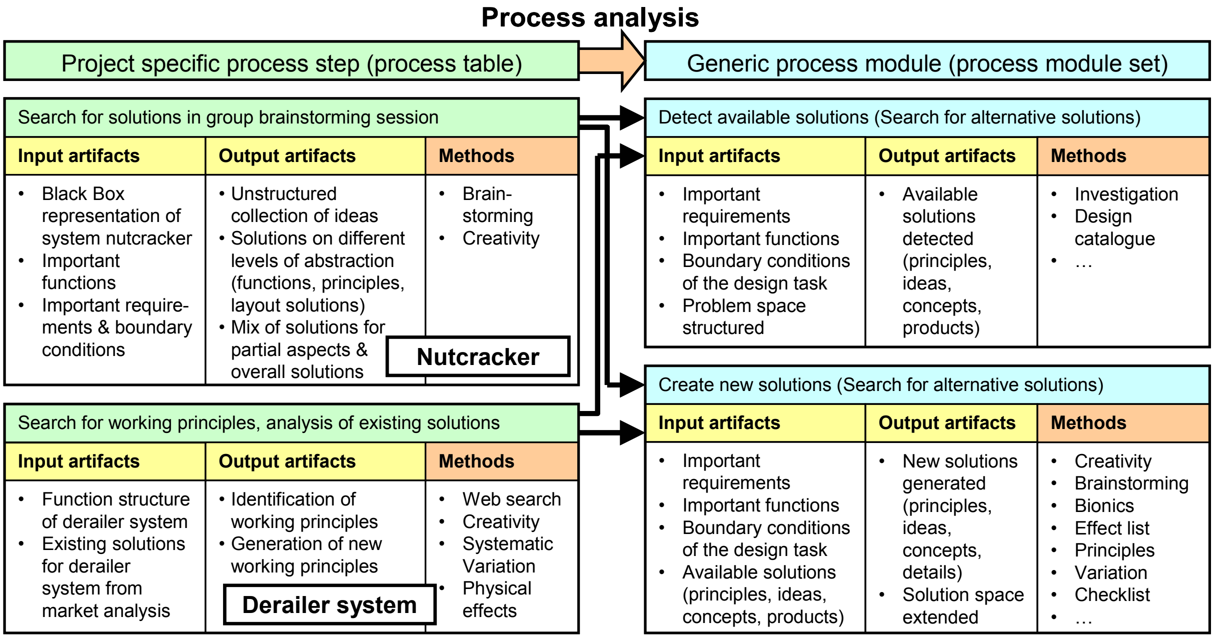

Figure 4. Comparison of real process steps with general process modules (Example)

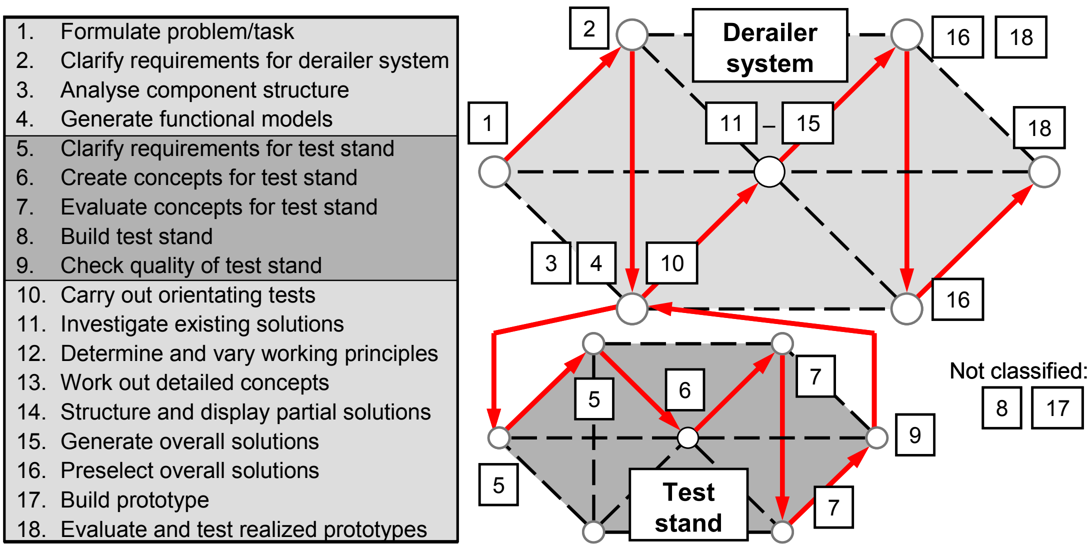

Figure 5. Process pattern (on superordinate level) in the case study “derailer system for recumbent bikes”

6.2 Process Planning and Control

The application of this concept for the purpose of process synthesis is done by configuration of entire procedures (chains of process steps) out of the available process modules. Project plans or procedural models usually contain proposed logical sequences of process steps on a higher level. On an operational level, a designer might be uncertain of what concrete steps to take next. By defining the situation, especially the status of task/problem, a tool based on the process module set can suggest adequate process modules. Even several chains of process steps can be generated. Anticipated output artifacts of one process module can be compared to necessary input artifacts of other process modules. By doing this, possible alternative process chains from problem to solution in a given situation can be developed. How far a process can be planned in advance on this level, remains to be investigated. To each process step methods are assigned which help to improve the quality of proceeding and outcome. In most cases, several alternative methods are available. The recommendation of the most appropriate methods is possible based on the situation characteristics. Moreover, a database of analyzed projects can offer relevant use cases. The relevance can also be based on situation characteristics (e.g. similar task, similar designer characteristics etc.). By looking at how certain tasks were carried out in other projects, which methods were selected and applied to achieve certain goals, and what results they delivered, positive effects are expected for current projects concerning systematic proceeding and successful method application.

7 Conclusions

The presented approach contains two major elements: a classification of design situations and processes as well as a set of generic process modules. Hereby, design processes can be analyzed and configured on a detailed level and in a flexible way. Exemplary use cases can be extracted from past projects in a standardized way by comparing specific process steps with the generic process modules. Hereby, the quick access to process and method knowledge is facilitated. To evaluate the utility of the concept and derive further potential for research, some aspects are discussed in the following.

Quality of contents of the process module set: The development of the initial process module set represents a top-down approach since the process modules were derived from a procedural model (MPM). The continuous comparison to real projects is a bottom-up approach to review, if the generic process modules correspond to real processes. Thereby, the process module set is updated. It has to be emphasized that a complete coverage of design activities of any kind is not possible with the 30 process modules defined here. Some processes that were identified in the case studies could not easily be assigned to a process module. When is comes to activities of embodiment and detail design, the process module set is not suitable to describe these processes adequately. By structuring the process modules according to the Munich Procedural Model, a “problem solving” perspective was generated. By including the contents of other procedural models, different views and new process modules could be added.

Process analysis of completed projects: The identification of process patterns, the evaluation of project results and the demonstration of method application on a specific topic can lead to valuable conclusions and recommendations for future projects. However, it is of major importance to bear in mind, how the design situation of the consulted case is characterized before insights are transferred to new (and therefore different) situations. Moreover, the suggested type of project analysis and documentation is time consuming. The retrospective view on projects leads to the extraction of valuable knowledge. A student’s semester thesis contains a lot of explicit information on a project. However, it is often very difficult to explicitly explain certain actions, how ideas were generated or why certain decisions were made. Students are instructed to include reflective thoughts on proceeding, method application, quality of results etc. Still many details are not documented. Projects in industry feature severer boundary conditions (e.g. time and cost pressure). The possibility of a transfer of the concept into an industrial environment yet has to be investigated.

Support of process synthesis: a tool based on the process module set can only give recommendations to facilitate the designer’s choice of action. An automation of the process planning is neither anticipated nor realistic. However, the user is able to manually choose from several suggested alternatives in the proceeding, which leads to a more guided navigation through the entire design process. Further research is planned with respect to working out the details of process planning and controlling strategies by means of the defined process modules. Another focus lies on the development of a corresponding software tool.

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