NordDesign 2012
August 22 – 24, 2012
Aalborg, Denmark

Bringing Knowledge Oriented Engineering to Design Practice

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Abstract
The significance of knowledge in the process of engineering design is often underestimated, disregarded in methodologies or neglected due to operational constraints.
This paper presents knowledge oriented adaptations to the scientific engineering process model of VDI 2221 as well as a knowledge oriented reengineering approach to be applied on real industrial design processes.

Keywords: Knowledge Management, Knowledge Oriented Engineering, Lean Product Development.

Introduction

Knowledge plays an important role in the process of engineering design. It is both driver and result of the design work. Its role and significance are however often underestimated. Therefore, holistic – sometimes even “philosophic” – approaches such as lean product development raise knowledge to a prime target of the design process, however omitting the provision of concrete tools or methods for operationalizing their goals [1]. With design to knowledge, such an operationalization approach was proposed in [2] by transferring the main ideas of lean product development onto concrete design processes. In this context, the knowledge stream analysis has provided an in-depth process analysis method to identify potential knowledge losses as well as respective improvement levers along the design process, exemplified on the process model of the VDI guideline 2221 [3].

This paper takes these ideas further and focuses on applying them on design practice. For this, it proposes knowledge oriented methodology adaptations on both a macroscopic and a microscopic level, first. On a macroscopic level, the step sequence of the VDI 2221 process model is revised by adding and adapting process steps. On a microscopic level, contemporary design methods generally applied along the process are revised to better support a knowledge oriented engineering process. Then, taking the results into account, the paper presents a reengineering approach to analyze real design processes with regard to knowledge aspects, and to conclude respective process and method adaptions, afterwards.

This article is structured as follows. Chapter 2 will set the frame by elaborating on the role of knowledge within the design process and discussing previous approaches underlying this work, which focused on analyzing contemporary design process models regarding their knowledge orientation. As these models still lack regarding their acceptance in industry (e. g. [4]), the results are analyzed with special regard to their applicability in design practice. Chapter 3 derives core ideas and principles to be incorporated into a knowledge oriented engineering design methodology, first. Then, it discusses a revised methodology based on these principles, introducing adaptations on both a macroscopic and a microscopic level.
Chapter 4 will incorporate these findings into a reengineering approach, which has been developed as a consulting tool for real design processes. As one key method, it applies a

knowledge stream analysis to efficiently identify knowledge oriented gaps and potentials along the process steps applied, which are then to be addressed in follow-up improvement steps. Finally, in chapter 5 the results will be discussed and conclusions will be drawn.

2. Knowledge within the design process

Traditional design methodologies generally focus on delivering products within defined time, quality and cost limits. Design process steps such as described in [3] lead to this goal by identifying, concretizing and finally realizing the best-as-possible solution principle for a product. Knowledge within these methodologies is however not assigned a prominent role, leading to only focusing on the product-related portion of the knowledge generated throughout the process, see figure 1.

2.1. Role of knowledge in design methodologies

According to the analysis described in [1], knowledge is seen in traditional design methodologies as – if at all – helpful input to the design process, e. g. by using supportive knowledge-based-engineering tools. It is not seen as something to be systematically built up during the process, not as a deliverable as such.

This can be seen from the example of the design guideline VDI 2221 of the German Engineers' Association. This standard provides a process flow beginning with a development task set out by product planning and ending with product documentation ready for further realization. It is thereby laid out to fulfill one predominant goal: getting a product idea realized. Looking in detail inside VDI 2221 and its subsidiary guidelines 2222 and 2223, knowledge is explicitly mentioned just twice – first in the sense of supporting the search for solution principles by using solution catalogues, and second in the sense of the provision of design rules in the context of the embodiment design phase. Creation of such rules or catalogues is to be covered by a separate process not being a part of the design process itself. Thus knowledge seems to be understood just in a sense of knowledge provision and usage, not in the sense of (formalized) knowledge capturing, creation and reuse. Similar findings apply to other contemporary methodologies; see the analysis in [1].

In contrast to this traditional understanding, the upcoming lean product development paradigm puts knowledge into the center of the design process, thereby suggesting adaptations also to the traditional design methodologies and frameworks. [1] refers to this concept as knowledge oriented engineering (KOE), and proposes to raise it to an underlying paradigm for the whole design process.

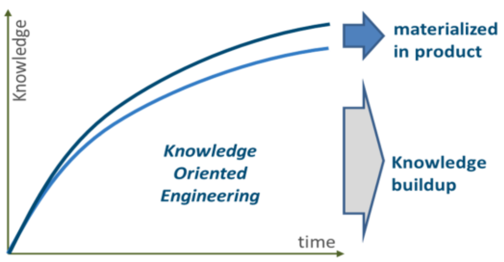

Figure 1: Product vs. knowledge as design result [2]

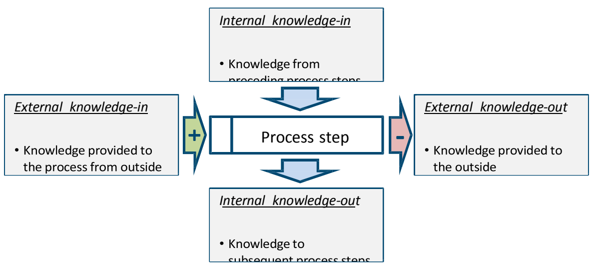

Figure 2: Knowledge stream analysis block for a general process step [2]

2.2. Knowledge oriented engineering

Although knowledge does not seem to play a prominent role in traditional design methodologies, it is a topic researched and discussed within a variety of product development related methods, some of which will be described in the following in order to delimit them from the approach presented in this paper.

Knowledge based engineering
Knowledge based engineering (KBE) is a quite popular term. It is used mainly to describe efforts of design automation based on captured explicit knowledge. It thereby makes knowledge applicable, but it does neither focus on the capturing of knowledge nor, in the sense of this paper, on making it a design target, itself. It has thereby to be distinguished from broader concepts such as knowledge oriented engineering, which is the basis for the process approach presented in this paper.

Lean product development
Lean product development is a philosophy originally erected on Japanese product development practices. Its core idea is a transfer of lean production ideas to product development, leading to a special honoring of knowledge along the design process. It thereby sets the philosophic ground for the knowledge oriented engineering paradigm and the knowledge oriented process approach presented in this paper.
In [1] knowledge oriented engineering has been introduced as a framework for the operationalization of knowledge-focused concepts like lean product development. This framework has been further detailed through the design to knowledge approach presented in [2], which has also introduced the method of knowledge stream analysis.

Design to knowledge
Design to knowledge targets an operationalization of the knowledge oriented engineering paradigm. It proposes to see knowledge as a target and focal aspect of the design process, thereby setting it as a second design deliverable aside to the products generally focused on. A significant ratio of knowledge generated throughout the design process may be wasted if the focus would be put on the product outcome, only, see figure 1.
Applying design to knowledge requires two main steps. First, the knowledge stream throughout the design process has to be identified. To achieve this, each process step has to be analyzed regarding the entirety of its inputs and outputs, see figure 2. Second, concepts have to be developed in order to make use of this knowledge, if applicable. E. g., methods or tools could be established to capture the side knowledge and make it available for further reference in future design projects. Generally, this approach targets to be applied as a process analysis and synthesis tool in order to improve real design processes as proposed in chapter 4. However, it can also deliver valuable conclusions when applied on theoretical process models such as VDI 2221, as pointed out in [2].

Knowledge stream analysis
This method analyses the knowledge stream along design process chains using flow diagrams as depicted in figure 2. It provides a powerful tool to identify knowledge related gaps in the process and thereby to prevent unwanted knowledge losses.
Knowledge oriented engineering targets to bring these concepts together and to thereby provide a framework for engineering design, which honors knowledge according to its significance for the product creation process. [2] drew first conclusions from applying knowledge stream analysis on contemporary design methodologies; in the following, these findings will be taken further and core principles for a knowledge oriented design methodology will be derived.

3. Knowledge Oriented Methodology

Knowledge oriented engineering builds on the following base principles to enable successful knowledge build up and usage during engineering design [1]. These principles are major distinguishers of knowledge oriented engineering from the traditional methodologies. Thus they build – through further operationalization in chapter 3.2 – the basis for the knowledge oriented methodology approach presented in chapter 3.3.

3.1. Base principles

Knowledge as a deliverable
Knowledge has to be honored as a core outcome of the process coequal to the product itself; knowledge is not to be wasted but to be captured and made reusable systematically. Traditional frameworks may therefor talk about knowledge based engineering, in contrast to knowledge oriented engineering as promoted by this paper.

Decisions late and sound
While traditional frameworks seem to see decision making as something desirable the earlier the better to banish uncertainty from the process, knowledge oriented engineering intends to keep decisions open as long as possible to base them upon a highest as possible certainty.

Innovation/performance separation
Lean product development distinguishes knowledge creation (innovation) and product creation (performance) as two independent, but inseparable value streams within the product development process. This implies dedicated organizational and project managerial approaches for both streams. Especially, the distinct focus (also) on the innovation (i.e. knowledge generating) stream is an essential element of knowledge oriented design.

Process scalability
While academic frameworks focus on new development projects and therefor provide methods especially supporting those, knowledge oriented engineering has to offer a toolset for both new and adaptive designs, both relying on knowledge in (potentially) different ways.

3.2. Operationalization concepts

Operationalization of the base principles described gives hints for adapting process models and methods applied along them. This can be supported by the following concepts.

Capture design and decision reasoning
According to the knowledge stream analysis described above, the reasoning behind design steps and decisions builds a significant part of the knowledge potentially lost (figure 1). Operationalizing the principle of *knowledge as a deliverable* has therefor to focus on capturing knowledge from design reasoning for reuse, see #1 in figure 3, and to provide tools and methods, accordingly.

Keep decisions open
Previous works have shown that, in traditional design frameworks, decisions are made early in the process in a way that a significant amount of knowledge is generated afterwards and thereby not taken into account in the decision process. They may therefor turn out to be suboptimal, later, or even be revised resulting in additional work and time effort.
Thus, operationalizing the principle of *decisions late and sound* has to focus on decision points within the design process, and the knowledge buildup before and after these points, see #2 in figure 3.

Besides these concepts described, IT may provide techniques to support integrated knowledge capturing along the process. As a basis, design objects along the process have to be consistently defined and captured including their interrelationships, see #3 in figure 3.

3.3. Knowledge Oriented Methodology

In the following, the base principles and operationalization concepts will be incorporated into a knowledge oriented rework proposal for the VDI 2221 process framework. Similar adaptations apply for other contemporary design methodologies.

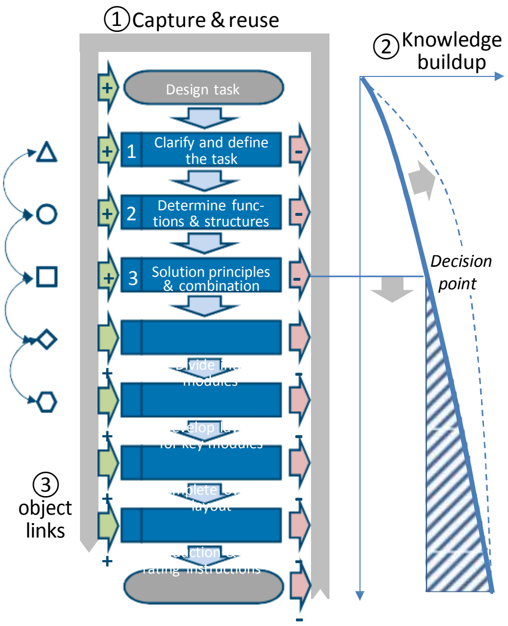

Figure 3: Improvement potentials along the product design process of VDI 2221 [2]

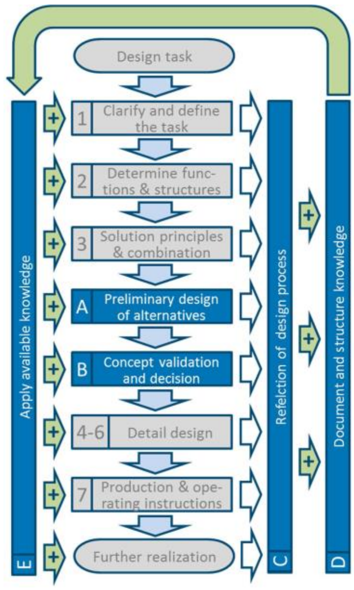

Figure 4: Knowledge oriented process framework

Figure 4 shows a process flow that aims to further develop the VDI 2221 process towards a knowledge oriented design methodology, with main differences being highlighted. This process takes the results of the knowledge stream analysis from [2] into account and incorporates the principles and concepts derived in chapter 3. In the following, a step by step description of this process in comparison to the corresponding VDI 2221 steps will be given.

Clarification and definition of the problem, determination of functions and their structures
These two steps are mainly taken over from VDI 2221 and target to derive a comprehensive specification of the product to be developed, first, and a functional description, afterwards.

Search for solution principles and their structures
With this step, the VDI framework proposes to move from the abstract function to a concrete geometric solution level, and to finally decide on an overall solution concept to be further detailed. The approach proposed here distinguishes from that understanding by keeping this decision further open. As a consequence, a number of different overall solution concepts may have to be followed up upon. Reflecting the set-based engineering thinking of lean product development [5], decisions are at this point only done in a way to exclude clearly inferior concepts, but to further follow up upon the others until enough knowledge has been built up to support a really sound concept decision.

Preliminary design of the alternative solutions
While VDI 2221 would continue with the division into and development of the key modules of the solution concept selected, the approach proposed adds two intermediate steps. With these steps, the alternative concepts are successively further elaborated until a preliminary design level is reached which is sufficiently mature to support a sound concept decision.
This proceeding supports the *keep decisions open* concept described above. It may add additional effort at this stage compared to the VDI process. It however targets to widely eliminate iteration cycles from later concept changes, and thereby to save on the overall effort, at the same time reaching a superior level of concept quality.

Concept validation and decision
As a consequence, concept evaluation – potentially supported through a test and/or simulation

based validation – is dedicated a separate process step. It leads to the final concept decision which can then be further elaborated in the subsequent process.

Design of the entire product, prepare production and operating instructions
These two steps incorporate the design steps 4 to 7 of VDI 2221 and lead to a design solution ready and documented for production and later use.

Further realization
This step is similar to the respective VDI one. It is however not seen as a follow-up step of design, but as an integral part, which is an important provider of lifecycle knowledge about the product.

Reflection of the design process
The process flow of figure 4 adds further steps on the horizontal axis to the sequential base process to establish a control cycle based on the horizontal knowledge streams through each step. This replaces the simple iteration cycles of VDI 2221 and operationalizes the knowledge value stream of lean product development. Within this reflection step, knowledge gained within the product value stream is systematically captured for follow-up documentation steps. This especially includes, according to the operationalization concept described above, knowledge from *design and decision reasoning*.

Document, structure and apply knowledge
These steps target to make the knowledge from the reflection steps explicit to be fed back as input to follow-up projects and processes.
With this process framework, a methodology is proposed that develops the process flow of VDI 2221 further towards a knowledge oriented design methodology. It focuses on capturing knowledge from the output side of the design process including design and decision reasoning and on feeding it back into the process on the input side. It considers postponing conceptual decisions to later steps in the process when the knowledge maturity is much higher to make sound decisions, and to prevent later change-based iteration cycles. In a next step, methods will be described which support this knowledge orientation on a more microscopic level.

3.4. Knowledge Oriented Methods

Along the design process, a multitude of methods is proposed to be applied. [6] provides an in-depth review of contemporary methods with concern to their dealing with knowledge. Based on this analysis, knowledge oriented method adaptations can be developed. Examples will be proposed in the following.

Knowledge oriented requirements specification
From a knowledge oriented standpoint, requirement specifications have to be enhanced in a way that background knowledge to each requirement can also be captured. This can be the source or author of the requirements, additional documents or any information that explains why a requirement was formulated and weighted as documented. This reasoning has to be updated all along the design process and further maintained all along the product's lifecycle.

Knowledge oriented solution finding
According to the *adapt methods for adaptational development* concept described above, solution finding methods have to be enhanced towards knowledge oriented methods applicable for both new and adaptational designs. The TRIZ contradiction matrix, e. g., can be adapted and extended to not only list abstract solution principles, but to also guide to concrete solution examples.

Knowledge oriented concept selection
One key method applied during concept selection is the morphological chart, which visualizes

the combination possibilities of the solution proposals for each sub function. From a knowledge standpoint, this approach is helpful to keep track of a wide solution portfolio. It however does not support capturing any reasoning behind. To achieve this, it is proposed to add to each partial solution a column for the documentation of advantages and disadvantages, limitations and tradeoffs as well as decision relevant properties and general reasoning otherwise not captured and thereby potentially lost. Furthermore, it makes sense to also documents evaluation and decision criteria specific to the project, which may explain any tradeoffs why specific solutions are or are not chosen.

Knowledge oriented project reflection

The reflection process step in figure 4 targets on the systematic capturing of all knowledge that may leave the process according to the knowledge stream analysis described above. This step has therefor to be supported by methods that help making knowledge explicit and documenting it in a way adequate for reuse in follow-up projects. One such method would be to systematically maintain solution catalogues through reflection in design review meetings. Such catalogues differ from contemporary design catalogues as they collect and provide proven concrete solutions and not universal abstract principles, such as provided by [7]. While the latter are valuable tools for new development tasks, the former are especially designed for supporting adaptational or variant design tasks. Beside the concrete solution, they contain advantages and disadvantages as well as limitations and tradeoffs, similar to the information already covered by the adapted morphological chart presented above. Information could therefor initially be added to these catalogues from the morphological chart in the solution finding phase, but would have to be maintained based on all experiences gained in later steps of the design process and all along the product's lifecycle.

Looking at the methods described, it becomes obvious that their knowledge oriented adaptions do not come for free – additional work has to be motivated for through a knowledge oriented culture with knowledge oriented targets honored equally to product oriented ones. This is a prerequisite for such methods to perform, if realized traditionally or – as popular in KBE approaches – on a Web 2.0 level being of secondary importance.

4. Knowledge Oriented Reengineering Approach

While chapter 3 focused mainly on the adaptation of the academic process model of VDI 2221, the knowledge oriented engineering concept presented also supports a knowledge oriented reengineering approach for industrial design processes.

According to figure 5, this approach would require an in-depth process analysis as a basis, first. Based on a – potentially already existing – product development process description, each step is undertaken a knowledge flow analysis. In workshops, the knowledge gaps and losses identified are then discussed and prioritized, and method adaptions are derived and planned. Finally, the new methods are implemented and the results are monitored. To be successful, this process has to be accompanied by an effort to foster a knowledge-promoting culture, which can be supported through a parallel set of workshops.

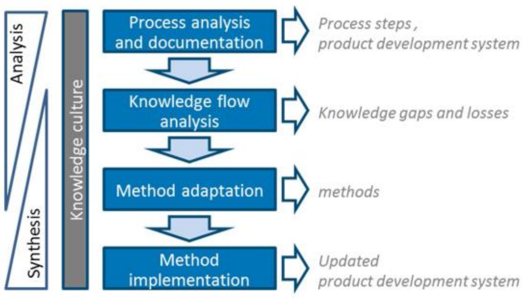

Figure 5: Knowledge oriented reengineering approach

5. Discussion and Conclusion

In this paper, a knowledge oriented design methodology has been developed starting from the paradigm level of lean product development, which puts knowledge into the focus of product development. This methodology has been applied on the VDI 2221 framework, first, and further developed into a knowledge oriented reengineering approach.

Compared with contemporary interpretations of the underlying lean product development philosophy, which fosters a separation and sequentialization of a knowledge value stream and a product value stream, the framework presented here shows an integrated approach to knowledge and product creation. The solely product oriented VDI process has therefore been enhanced by adding additional process steps, and by reinterpreting others.

It has however also been explained that all knowledge related effort heavily relies on a knowledge oriented engineering culture, which may also explain today's differences in knowledge thinking in Japanese and Euro-American companies.

While the process flow developed shows significant knowledge oriented improvements to the underlying VDI 2221 one, it is not meant as a direct replacement proposal. Nevertheless, it proposes changes to be considered as part of a broader rework effort, which would also have to take other developments in the area of product development into account – e. g. the ongoing mechatronization of the products, the rising focus of ecological aspects, and the virtualization of the development and validation processes. However, [2] has shown that knowledge plays a superior role in the optimization of product development processes, as it provides a root design principle, putting others in a secondary row.

Furthermore, a reengineering method has been described to bring knowledge orientation to real engineering processes. While a multitude of concepts and tools for knowledge management in engineering exists, a deeper implementation and acceptance in practice often fails due to practical, organizational or cultural reasons. The approach presented targets on focusing concrete gaps in and adaptions to living engineering processes, thereby making a sustainable implementation and acceptance more probable and potentially more successful.

Future research will focus on further detailing the process model and the adaptations of its methods, leading to a knowledge oriented process guideline and toolbox both capable to serve as a scientific process model and an improvement tool for real industrial design processes.

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