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Analyzing iterations in mechanical design processes – a method for data acquisition in meso-level studies

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Abstract

Mechanical design is the process of defining a mechanical system for a specific behavior. To support mechanical engineers in their tasks, research in studies on the design process is important. Currently there is a lack of meso-level studies on iterations in mechanical design research. We propose a documentation method for such studies. Target of the method is enable identification of iterations in mechanical design processes. Iterations occur regularly in design processes and can have an impact on project cost and quality. Therefore, they can be used to identify methodical need. We apply the method in three mechanical design projects and show its suitability for mechanical design process research.

Keywords: Design Process Research; Iterations; Meso-Level; Research Method; Mechanical Design

1. Introduction

In design processes of mechanical systems, mechanical engineers define the embodiment of the product. Mechanical engineers need to consider limitations and possibilities of manufacturing and fulfill criteria such as limited cost of design, time to market, usability and other restrictions or requirements. A single mechanical engineer or a small team of mechanical engineers as part of a design team typically conducts this task.

Particularly interesting design processes for mechanical systems is the development of mechanical components to achieve a specific product behavior. During this process, mechanical engineers need to understand the relationships between parameters of the embodiment and the products behavior. The necessary knowledge is gained throughout the design process.

Mistakes along this process can lead to costly iterations when they are discovered in late stages of the product development process [1]. An example for such mistakes from recent research is the false identification of problem causes due to cognitive biases [2]. Meboldt et al. [1] state that along a stage gate process, iterations are necessary in the design process. They also state that costly iterations are iterations across gates and after a product entered the market. This complies with the classification of Wynn and Eckert [3] for iterations, who differentiate between progressive, corrective, and coordinative iterations. Research on iterations provides valuable insight in the design process, as iterations influence project costs and occur regularly in design projects. Therefore, they can be used as an indicator for methodical need, which could be addressed by design research.

There are mainly two types of studies in design engineering. First, there are small protocol studies with short durations to research individual behavior. Second, there are large-scale studies analyzing complete processes to research management questions on a macroscopic level. Studies on projects that are on a level between these two types of studies, meso-level studies, are rare in design process research [4]. Wegener and Cash [4] analyze design process research and show this gap in further detail.

In this contribution, we aim at providing a method for meso-level process research on iterations in mechanical design. The research method must meet the following requirements:

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- allow a study with several participants working at the same time,
- allow observation over a realistic duration of several months,
- applicable independent of the design project,
- allow identification of iterations,
- record information about specific activities as well as the overall process,
- allow qualitative as well as quantitative data evaluation.

In the following, we present studies on the micro-level and macro-level on iterations in design with focus on the methods that were used for data acquisition. On the micro-level Smith and Tjandra [5] researched iterations in design processes by observing student design teams while solving a task over the course of two to three hours. As data acquisition, videos were recorded and coded for evaluation. Iterations were identified as analysis synthesis cycles. Adams and Atman [6] followed a similar approach. Students were given a design task and a verbal protocol was recorded. Based on the transcript of the process they find that students who conducted deeper problem scoping achieved a better quality in the design task. Atman et al. use the same approach in a study comparing experts and students on a larger group of participants [7]. Jin and Chusilp [8] conduct a study on mental iterations in design. They use the think-aloud method to record the activities of the participants. Each participant works on two tasks. A creative and a routine design task. They find the existence of global and local iteration loops within the cognitive activities in a design process. While these studies allow detailed insight in the individual design processes, the data acquisition is limited to studies with tasks that can be completed within several hours. On the macro-level, there are single case industrial studies on design engineering. A team of researchers often conducts such studies over several years. Piccolo et al. [9] conduct research on the role of iterations in large-scale design projects. They collect and analyze documents created during design of a biomass power plant. This kind of data collection allows network analysis to draw conclusions from testing hypothesis based on a large amount of data. However, this requires a long period of data acquisition and an infrastructure to acquire documents. Badke-Schaub and Frankenberger [10] research teamwork in design projects. The researchers record the activities of a design team through observation, interviews, document collection, diary sheets and questionnaires. Through this combination of direct and indirect data acquisition, they were able to record the full design process. Direct observation of a design team requires many resources from researchers. In contrast, a combination of direct data acquisition through participants and indirect data acquisition via interviews offers a more efficient approach. The analysis of complete design projects, as in the examples, always includes interdisciplinary questions, as well as social aspects of teamwork as in Badke-Schaub and Frankenberger's study.

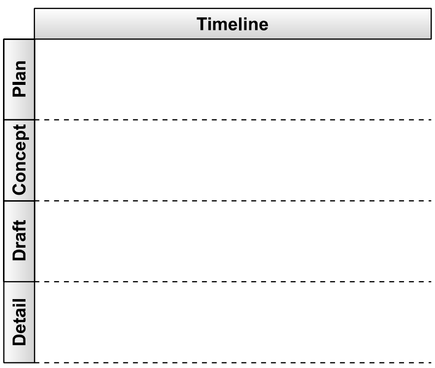
We conclude that there is a lack of study designs for meso-level research on iterations in mechanical design projects.

Aim of this paper is to present a method for data acquisition in mechanical design projects on a meso-level of detail. We use a swim-lane diagram approach to document the process in combination with a diary sheet and collection of documents through the participants. The process is only accompanied by the researchers and not actively observed. To evaluate the documentation method, we conduct a small study with 3 participants. Aim of the study is to evaluate the method's ability to identify iterations in the process. The method can be used in further studies to identify methodical need in mechanical design projects based on quantifying the iterations.

2. Data acquisition method

In the following section, we describe our data acquisition method. This includes the underlying process model, means of documentation and data evaluation. Fig. 1 shows the elements of the data acquisition method. We use a swim-lane diagram with flow-chart symbols for process visualization and a diary sheet for further information on the activities.

Seow et al. [11] use a design process model to map complete design projects based on assigning activities to the phases define, discover, develop, and deliver. To do so, they record activities and the work hours for each activity. Result of the data collection is a spiral diagram of the design process called design signature. We adapt the idea of using a process model to mechanical design processes in which different types of iterations can be identified. The documentation method is based on the design process model of the VDI-2221 [12]. In the VDI-2221 the design process is defined as a set of activities carried out by the design team. Each activity is placed on the



Activity	Description	Created Documents	Duration
#-Phase-PartCode	Free text description of the activity	Names of or links to created documents	Duration of the activity

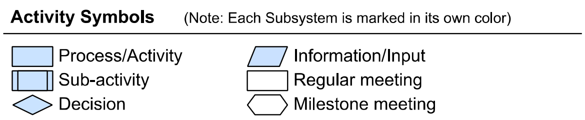


Fig. 1. Left side: Template of the swim-lane diagram with the four phases of the design process. Right side top: Template of the diary sheet. The activity column is filled with a coded name containing the number of the activity, an abbreviation for the phase, and a code for the system or subsystem in focus of the activity. The duration of the activity is documented in days.

timeline and assigned to a phase. The phases depend on the system under development and the type of project. We adapt this mapping of process activities and use phases to cluster activities to create a swim-lane diagram along a timeline.

The swim-lanes represent phases of the mechanical design process, adapted from examples in the VDI-2221-2 and phases of the product development process defined in Pahl/Beitz [13], see Fig. 1. The hierarchy of the phases is defined by the theoretic linear process. In the swim-lane diagram they are used to cluster activities and visualize the iterations, see Fig. 2. The phases are simplified and limited to the project goal of a detailed design ready for manufacturing a first physical prototype. Through the clustering of activities, the swim-lane diagram will show how early activities are repeated in a later phase of the process and through this identifiable by the researchers.

The *plan phase* is the swim lane for early activities, for example research, system analysis or problem scoping. The *concept phase* includes activities for finding approaches to solve the design problem. The *concept phase* includes among others the application of creativity techniques to generate solutions or the development of concepts with qualitative models, such as sketches. In the *draft phase*, all activities contributing to defining the quantitative design are gathered. The *draft phase* can be further divided in a *subsystem* and a *main system* phase if applicable. The typical transition from concept to draft is done by creating CAD models or by dimensioning key elements of the concept. The *detail phase* includes all activities that are necessary to completely define the product. This includes, for example, the creation of a documentation for manufacturing or the final integration of all subsystems in the main assembly.

To create the swim-lane diagram, participants need to document their activities. Activities are defined as work packages that are necessary to continue the design process. Most activities end with the creation of a deliverable. Examples for activities in the target design processes are research, drafting concepts, create a CAD model, dimensioning of components, and create manufacturing documentation. To further detail the activities, participants keep a diary sheet of their process. Additionally, the participants are given a guide line. The guide line explains the activities and phases in which the activities are clustered and how to assign activities to a phase. The participants keep track of their activities and assign

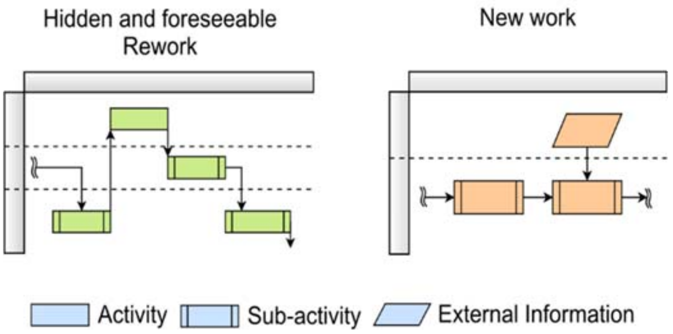


Fig. 2. Representations of rework and new work iterations in a swim-lane diagram. The definitions for the iterations are according to Wynn and Eckert [2].

them to the phases. The framework of the diary sheet is shown in Fig. 1.

Initial analysis will be conducted based on the activities, their order and their duration. Detailed analysis is based on the created documents in the activities. To fill gaps in the process or gather more detailed information on identified iteration cycles, a debriefing interview with the participants is recommended.

We analyze the participants' design processes regarding the types of occurring iterations. For this purpose, we define iterations following Wynn et al. [14] and the expansion by Wynn and Eckert [3] through literature reviews. These studies define three classes of iterations: *Progressive iterations*, *corrective iterations*, and *coordinative iterations*. *Progressive* and *coordinative iterations* are necessary to achieve the project goals. An example of *progressive iterations* is iterative testing, which can be necessary to build a better understanding of the systems behavior. C*orrective iterations* occur when activities need to be repeated due to errors or the project progress is set back by unexpected events [1].

To identify iterations in the swim-lane diagram, their appearance is predefined in a data evaluation guideline. Iteration cycles are identified through comparison and marked in the diagram. The iterations are analyzed further for qualitative insights. For quantitative data evaluation, activities and number of documents are counted as well as the types of iterations according to the definitions of Wynn and Eckert [3].

Fig. 2 shows the representation of rework and new work in the swim-lane diagrams, through which they are identified. Rework is the re-iteration of a sequence of identical activities [3]. For our investigations, we use the distinction between hidden and foreseeable rework, which was established by Zhang et al. [15]. New work is an activity that is described by the participant as not initially planned. In the presented case, new work is caused by an activity placed in an earlier phase. New work iterations should be verified in the debriefing interview.

3. Evaluation study

To evaluate the documentation method, we used three design projects of students. The design projects are part of a thesis of mechanical engineering students in their 6th semester. Each design project takes three months. All students had to do the mechanical design of a system as part of their thesis. Aim of each project is a design that allows for the manufacture of a first physical prototype. The three design projects were not connected and were:

- Design of a sharpness measurement device for industrial slicing blades (SMD),
- Design of a test bench for research on vibrations in fast rotating gear systems (TB),
- Design of a bearing housing for a test bench with tunable stiffness properties (BSV).

The test bench design project was conducted by two students, working as a design team.

For each project, the participants created a swim-lane diagram of their process and filled out the diary-sheet. Based on this information, the swim-lane diagrams were evaluated for iterations. Finally, a debriefing interview was conducted with the students to clarify questions on the documentation and to fill gaps.

4. Results

All participants created a diary sheet and the according swim-lane diagram. Table 1 shows the number of activities conducted in the design projects and the number of generated documents. The number of generated documents remain roughly the same along all three projects. In contrast to the other projects, the test bench design process involves much more activities because two students conducted it.

Table 2 shows the results of the iteration evaluation of the projects. *Exploration*, *Concretization*, *Hidden Rework*, *Governance* and *Negotiation* occurred in all three projects. Activities carried out during *concretization* are component dimensioning, initial definition of the shape of individual components and their position within an assembly. These activities occur in all three projects. *Hidden Rework* is present twelve times.

Table 1: Number of Activities and Documents in the conducted design projects

	Sharpness measuring device (SMD)	Design of a test bench (TB)	Bearing seat with variable stiffness (BSV)
Activities	37	54	32
Documents	19	20	20

Table 2: Quantitative analysis of iteration in the analyzed design processes.

Iteration Clusters	Types of Iterations	SMD	TB	BSV
Progressive Iteration	Exploration	3	1	2
	Concretization	11	8	5
	Refinement	0	3	0
	Convergence	0	0	0
	Incremental Completion	1	0	1
Corrective Iteration	New work	1	0	0
	Hidden Rework	3	4	5
	Foreseeable Rework	0	1	0
	Churn	0	0	0
Coordinative Iteration	Governance	5	2	2
	Negotiation	2	6	7
	Parallelization	0	0	0
	Comparison	1	0	1

Eight out of the twelve hidden rework iterations were triggered by the regular communication of the designer with his mentor, called *negotiation*. We observe that five of these cases are caused by an initially incomplete requirements list. In the other three cases design flaws or potential for design optimization is identified as the cause. Two hidden rework iterations are triggered by milestone meetings. These iterations are caused by design flaws or optimization possibilities which are agreed upon in the milestone meeting. In the remaining two out of the twelve cases of hidden rework either no clear trigger can be assigned, or a self-detected error is documented. Further examination of the documents in context of the corrective iterations showed, that the project tasks and requirements were detailed along the process.

Fig. 3 shows the swim-lane diagram of the SMD project. In the evaluation step, types of iterations were identified by the researchers through comparison with the templates, see example in Fig.2. Each iteration is marked in the diagram with color coded fields, illustrating which activities are assigned to the iteration. This process is supported through analysis of the activity descriptions. The analysis shows three hidden rework iterations, two instances started through additional information achieved and one in a milestone meeting. Cause of these unplanned iterations were an insufficient quality of the design. This led to redesign and corrections in following process steps. Further analysis of the documents showed insufficient experience of the participants in designing mechanical components and adaption to manufacturing process specific needs.

5. Discussion

All three projects were documented by the participants. Tables 1 shows that the number of documents and activities is similar for all projects. The only exception for an increased number of activities is the TB project which was conducted by two students. Due to the similarity and duration of the projects we assume, that the documentation of all projects was done properly by the participants. The types of iteration occurring in all three projects suggest that there are issues that are independent from system specific tasks. The coordinative iterations *governance* and *negotiation* occur in all projects, as they are mandatory for the students. Whether *governance*, milestone meetings, or *negotiation,* technical meetings, occurred more often depended on the project structure and external conditions of the project.

As mentioned in the results, evaluation of the documents revealed that project tasks and requirements were detailed in coordinative iterations throughout the projects. We identified this as cause of hidden rework. The results of Adams and Atman [6] show a superior performance by students with improved problem scoping. Therefore, these iterations might have been prevented by spending more time in the planning phase to detail project tasks and requirements in an early phase. This is also supported by the results of Atman et al. [7], who showed that experts spend more time on gathering information and cover a broader range of categories during problem scouting than students. This shows that the method is

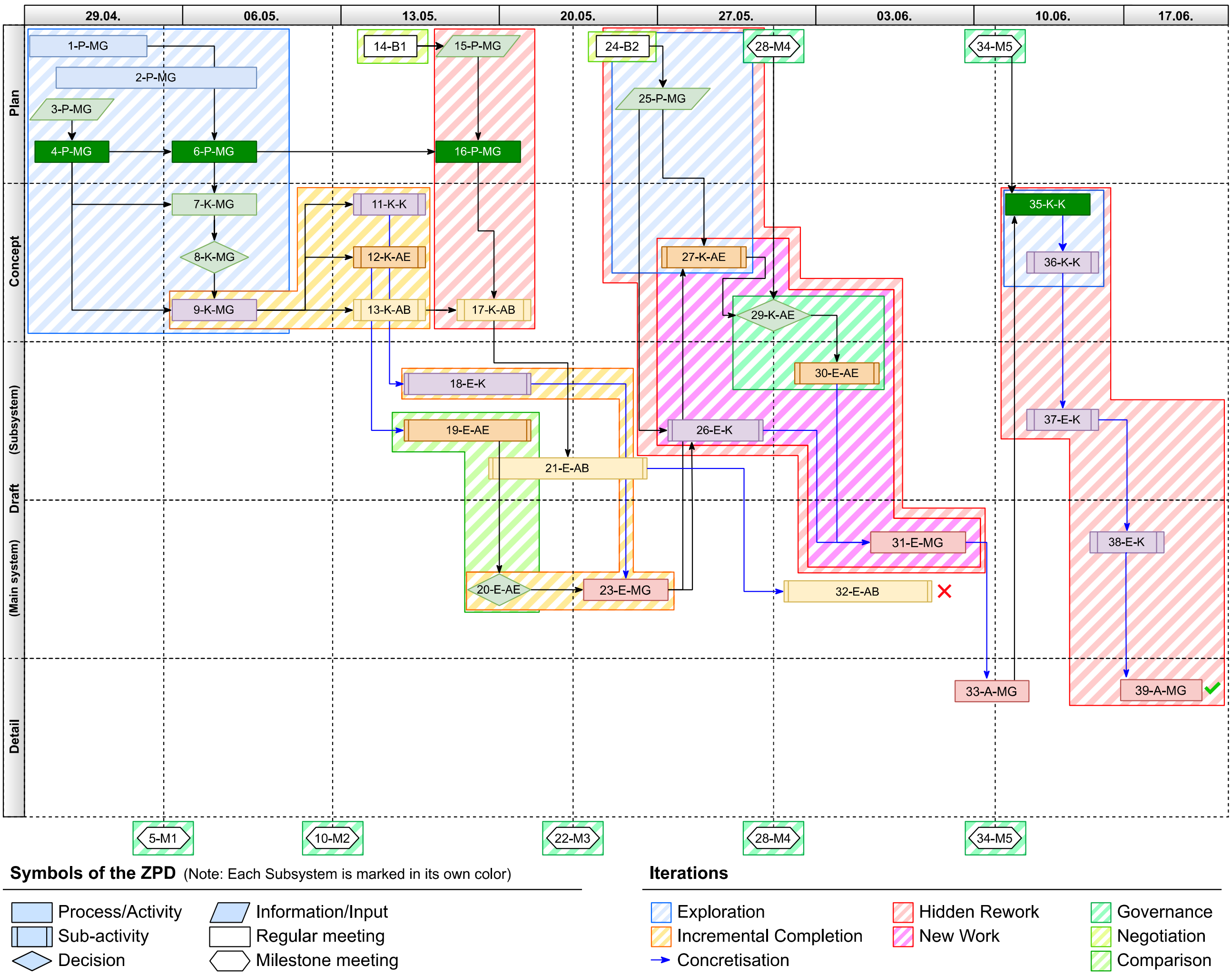


Fig. 3: Evaluated swim-lane diagram of the project industrial slicing blades (SMD). The red cross marks that the design process of the sub-assembly stopped at this point.

applicable to find realistic consequences of specific actions on the design process.

Iterations due to the inexperience of the participants in practical mechanical design were expected. For example, the iterations due to insufficient design quality for manufacture. In a further study, the created documents could be analyzed to find more detailed causes of iterations. An example would be an in depth analysis of the created concepts. Theses results would allow to propose methods to participants and prevent iterations in further projects.

The identification and interpretation of *progressive iterations* is less comprehensive compared to *corrective iterations*. Basically, all activities that are not part of a *corrective* or *coordinative iteration* could be interpreted as a *progressive iteration*. Therefore, we could not create further insight from evaluating *progressive iterations*.

Compared to the methods of other researchers, for example think-aloud, video-analysis, or large-scale document acquisition, the method has proven to provide a reasonable amount of data over the course of the projects. The data acquisition is possible without extensive work of the researchers for transcribing protocols, document analysis, or video analysis. On the other hand, the remaining ambiguity of the phases and assignation of activities showed, that interviews with the participants should be conducted to ensure the information is interpreted correctly and to gain further, unwritten information, compare to Badke-Schaub and Frankenberger [10]. Overall, the method seems to meet the requirements for a meso-level study to answer questions on a meso-level for mechanical design projects as "*how do specific early design actions influence later design actions?*" posed in general for design processes by Wegener and Cash [4].

Although the evaluation is in general considered successful by the authors, there are limitations. The application of the documentation method probably influences the behavior of the participants. Due to the documentation of the activities in the data table and the creation of the swim-lane diagram, participants automatically reflect on their process. This could lead to insights of the participants on the process and a change in their actions compared to working without documenting their process. Since these alterations should be limited to participants without experience in design projects and their structure, more experienced design engineers are expected to initially have a better structured process and therefore will not change their actions based on the documentation. Still, this should be investigated in further studies.

In addition, the subjective aspect of the documentation limits the evaluation. Quantitative evaluation and comparison are only possible with the number of iterations. Quantitative evaluation of activities is only useful if the research question aims at the activities. For example, if a hypothesis for the study states that participants with a more extensive exploration phase are more successful. While this could be accounted to the number of activities in the planning phase, it leaves the question if the quality of the conducted activities trumps the mere quantity. To improve the method, the ambiguity of activities and phases could be reduced by adjusting them to the design tasks.

6. Conclusion

The individual nature of design processes and often system specific challenges make it difficult to conduct research on the mechanical design process. In the present design process research, there is a lack of meso-level studies. In this paper, we present a research method for data acquisition in mechanical design projects on a meso-level to analyze the effect of individual actions on the design process. The method provides data for process analysis through documentation of activities by the participants. The documentation is a swim-lane diagram in combination with diary keeping. This enables researchers to identify iterations in the processes without the need to directly observe the participants. The acquired data is then analyzed for iterations. In a study with three mechanical design projects conducted by mechanical engineering students, we show that the approach produces data that can be evaluated in the intended way. Evaluation of the data showed that *corrective iterations* were caused by a lack of quality of the design or due to a need for further specification of project goals and requirements during the project. From these results we conclude that our application of the research method is successful. Since the data was successfully analyzed, we conclude that our approach is suitable to conduct meso-level studies on mechanical design processes. Future studies can use the data acquisition method to investigate the effect of applying methods on iterations the design process.

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