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Managing Assumptions during Analysis - Study on successful Approaches of Design Engineers

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Abstract (300-500 words)

The analysis of technical systems is the basis for a successful product development. Only a detailed understanding of the design problem allows the synthesis of a successful solution. To synthesize an improved design, the design engineer must mentally relate the system's function and behavior to the system design – a challenging task where many assumptions arise. We already conducted a preliminary study to identify success factors in the analysis. Based on the findings of this, we have set up the following hypotheses. (H1) A structured verbalization of one's own understanding of a technical system helps to identify gaps and mistakes in the own analysis. (H2) Verifying own assumptions about the function and behavior of a technical system improves the quality of the analysis. To test the hypothesizes we conducted an eye tracking study with two realistic design tasks, representing a functional analysis and a synthesis-driven analysis. Concurrent Think Aloud is used to elicit information on the participants' thoughts and insights. Eye Tracking is deployed to record the participants' point of gaze and therefore the area of the design, which the participant is analyzing. The combination of the Eye Tracking data with the transcribed Concurrent Think Aloud allows a detailed examination of the analysis approaches. After the participants finished the tasks, they answered a questionnaire to ascertain their understanding of the assigned problem. Success in the analysis is determined by the use of the participants explanation (functional analysis) and the questionnaire (synthesis-driven analysis). Two groups participated in this study to consider differences in the participants' experience - 11 design engineers and 13 mechanical engineering students. (H1) In the results we found no evidence that a structured verbalization of one's own understanding of a technical system helps to identify gaps and mistakes in the own analysis. (H2) We found evidence that verifying assumptions on a system's function and behavior enhances the completeness and correctness of the analysis. Although we also found a few cases, where the verification has led to worse results. It seems to be helpful to make several assumptions and to choose the most likely explanation based on the available facts. A procedure that seems logical but was only used by very few participants.

Keywords: Human Behavior in Design, Engineering Design, Functional Analysis, Comprehension Process, Product Design

1 Introduction

Product development projects inevitably involve iterations. While small iterations can advance the project, large iterations are associated with higher project costs and project durations. Many of these iterations are required because the development was attempted with imperfect information (assumptions). (Meboldt et al., 2013; Wynn & Eckert, 2017) The problem often occurs because "people feel they understand complex phenomena with far greater precision, coherence, and depth than they really do; they are subject to an illusion" (Rozenblit & Keil, 2002). A detailed analysis of the technical solution is necessary to overcome such biases. Dylla (1990) and Ehrlenspiel & Meerkamm (2013) emphasize the need for a thorough analysis of the technical system in order to achieve good design performance.

As we showed in an earlier study, a major problem during the analysis is to deal with these assumptions in analysis phases during design engineering (Matthiesen et al., 2018). There is a lack of methods, which support the design engineer in dealing efficiently with assumptions. To develop such methods, we investigate the analysis approaches of design engineers in empirical studies. By identifying successful approaches, we want to make them accessible to other design engineers.

In this paper, we would first like to give a brief overview of our understanding of the functional analysis (chapter 1.1) and the synthesis-driven analysis (chapter 1.2). This paper is based on a preliminary study we conducted earlier (see chapter 1.3) to formulate hypothesis. In this paper, we will present the corresponding main study (chapter 2) and the results of the tested hypothesis (chapter 3). This is to be followed by the discussion (chapter 4) and the conclusion (chapter 5).

1.1 Functional Analysis

Functional analysis or "functional decomposition is a process that is typically used to assist engineers with identifying essential functions in various design tasks, including product dissection. It is a valuable tool used in industry to improve legacy products, understand competitor products, or help new employees learn about a company design." (Booth et al., 2015)

Many researchers studied the functional analysis. Eckert et al. conducted a study on how design engineers analyze a hydraulic pump and how they represent their findings in a function tree. They identified that the participants used strategies like top-down, important things first, issue driven and energy-flow throughout the system. (Eckert, et al., 2012) Booth et al. studied which function identification method (energy-flow, top-down, enumeration) works best to build up function trees of before unknown systems but couldn't find a difference in the created function trees. (Booth et al., 2015) Hess et al. conducted an eye tracking study on a functional analysis task and identified that successful participants have a wider knowledge-base of technical systems. This knowledge helps the participants to understand functions without examining them in detail. It also helps them to identify and evaluate the importance of a system's subfunction. High performing participants verified their assumptions on functions whereas low performing participants did not. (Hess et al., 2017)

There is preliminary work in this area, which has investigated the analysis of unknown systems. However, it was not investigated how assumptions were verified in the analysis. During the functional analysis, many subfunctions are analyzed, and many assumptions are made. We have therefore included the functional analysis in our study in order to include a larger number of verifications.

1.2 Synthesis-Driven Analysis

The second type of analysis describes the analysis tasks during design engineering. Especially in late design phases design engineers already know the intended function of their system, because they created it. But in the later design phases problems occur because the system's behavior is becoming too complex and easier problems have already been solved. (Smith & Tjandra, 1998) Vibrations in the drive train or component failures are frequent problems in the late phase of product development. Previous studies do not cover these kinds of problems. They often focus on new developments. Problems that are analyzed here are more likely to be found in the concepts than in the engineering details.

To map such problems in laboratory studies, the participants have to further develop an existing system. For this purpose, they are introduced to a system and its intended functionality. The participants are given the task of further developing this system. To optimize the design solution, the design engineer must analyze these problems to find and solve the problem-cause. Ruckpaul et al. defined therefore the term synthesis-driven analysis. This type of analysis describes the process of design engineering, in which a design engineer analyzes to the extent that he can make the next synthesis step. (Ruckpaul et al., 2014) In contrast to this, synthesis is not the objective of the participants during the functional analysis.

We performed a study on differences between the functional analysis and the synthesis-driven analysis. Fundamental differences are shown in the overall analysis strategies. Whereas *top-down* and *energy-flow* are common overall strategies for functional analysis they were not present during the synthesis-driven analysis. On a micro-level the analysis approaches were yet comparable. (Matthiesen et al., 2017)

Synthesis-driven analysis provides a very good representation of the analysis processes in design engineering practice. Fewer assumptions are made in comparison to functional analysis, but it can be assumed that the external validity is higher. We have therefore included the synthesis-driven analysis in our study.

1.3 Preliminary Study and Research Hypothesis

To identify successful analysis approaches, we have carried out a preliminary study. It consisted of 2 tasks. 4 students and 3 experienced designers took part. The first task represented the functional analysis. The participants were supposed to recognize how a lawn sprinkler works. The second task represented the synthesis-driven analysis. The participants were supposed to optimize a power-tool. (Matthiesen et al., 2017) We had adopted the tasks of the preliminary study in this paper. The detailed presentation of the study will therefore follow in Chapter 2.

To verify the qualitative results of the preliminary study we set up the following hypotheses to test on a larger sample.

H1 A structured verbalization of one's own understanding of a technical system helps to identify gaps and mistakes in the own analysis.

In the preliminary study, we asked the participants to state their understanding of the technical system after the functional analysis. While the participants verbally explained the system, three students out of the seven participants had considerable insights on subfunctions of the system. They identified gaps and mistakes in their own understanding. All participants followed the energy-flow to explain the functionality of the system. We have concluded that this structured verbalization helped them to review their understanding.

In addition to our findings, Hacker showed that non-professionals have better design drafts, when they reflect their design verbally (Hacker, 2002). It is still unknown if the structured verbalization also improves the analysis processes.

H2 Verifying own assumptions about the function and behavior of a technical system improves the quality of the analysis.

The successful participants in the preliminary study were more aware that their findings during the analysis could be wrong. Therefore, they verified their assumptions (findings characterised by a certain degree of uncertainty) more thoroughly and examined different evidence/aspects of the technical system. False assumptions were detected and the participants were able to continue the analysis efficiently. Otherwise, incorrect assumptions often led to additional errors and long iterations in the analysis. Correct assumptions could be confirmed and gave the participants confidence. Frequently, the verification also provided a deeper understanding of the system. This factor has already been described qualitatively in the literature, but we do not know of any quantitative studies.

The quality of an analysis depends on much more variables, like the knowledge-base and the experience of the analyzing person. These factors were deliberately not the focus of our work. Knowledge and experience must be built up over an extended period. With the results of this study, it should be possible to give design engineers instructions that lead quickly to better analysis results. Even with such methodological support, experience will be a key factor. However, we also want to enable less experienced engineers to analyze with more success.

2 Experimental Design and Procedures

To test the hypothesis, we used the study design of the preliminary study. Figure 1 shows the experimental setup of the study (second task – synthesis driven analysis). The participants have a laptop in front of them showing a PowerPoint presentation. This presentation will guide the participants through the whole study. The second laptop is to monitor the eye tracking recording.

Figure 1. Experimental setup – synthesis-driven analysis (Matthiesen et al., 2017)

2.1 Procedure

We used 4 methods of data acquisition for both tasks: (1) mobile eye tracking to observe on which parts of the system the participants acquire information. For this paper, the eye tracking recording were only used qualitatively so that the coder could better understand the participants' approaches. (2) The participants were asked to use concurrent think aloud to elicit their insights and thoughts during the analysis. (3) After each task, the participants should verbally express

their findings from the analysis. (4) For better comparability, they also answered a questionnaire regarding the systems functionality.
The participants had to work individually during the study. In the beginning of the study, the moderator starts a PowerPoint presentation with the relevant information of the study and the two tasks. The presentation guides the participant through the whole study. With a short exercise before the tasks, the participant becomes accustomed to the concurrent think aloud. When the participant remains silent for a period, the moderator reminds the participant to think aloud.

First Task: Functional Analysis
The first task is to determine the functionality of a lawn sprinkler. Therefore, the participants get an original lawn sprinkler and a manipulated lawn sprinkler, which they can easily disassemble and examine the inside parts. The participants' task is to examine the functionality of the alternating mechanism. The participants determine the end of the task when they think they understood the mechanism. The moderator will determine the task after a maximum of 10 minutes.

Second Task: Synthesis-Driven Analysis
The second task is about the further development of a power tool. This task is based on a real problem. In the late development phase, a safety-relevant part fails in a test. The goal for the participant is to develop a suitable design solution - not explicitly the analysis of the problem. The intended function is presented in a PowerPoint presentation to give the participants the necessary knowledge to detect differences between the intended function and the actual behavior of the system. The participants receive the resources, which would also be available to them in a company: the power tool, the broken parts from the test, an enlarged model and a technical drawing of the relevant assembly group. The challenge with this task lies in the fact that the component fails by the strong recoil of the system and not by the movement which is necessary for functional fulfillment. The participants can determine the end of the task when they think they developed a suitable solution. The moderator will determine the task after a maximum of 20 minutes.

2.2 Participants

26 subjects participated in total. To consider analysis approaches of varying experience the study was carried out with low and high experienced design engineers. The low experienced group consisted of 14 mechanical engineering students who were at least in their 5th semester (mean 6.9 years, standard deviation 1.9). 12 male and 2 female students took part in the study. The data of one student was not used in this study, because he later said, that he already knew both systems of the study from a lecture. The experienced group consists of 12 design engineers with at least 2.5 years of experience (mean 12.4 years, standard deviation 8.5) in their field. Only male design engineers took part in the study. The data of one design engineer was not used in this study, because he was too unambitious during the tasks and abort the task without analyzing the systems in detail. In total, the data of 24 participants (13 students, 11 design engineers) were evaluated in this work.

2.3 Data Analysis

The goal of the analysis for H1 was to identify which additional insights or corrections of mistakes the participant had during their explanation of the system's functions after their analysis. After the analysis in task 1 (functional analysis) the participants verbalized their findings. The statements were evaluated according to whether 9 predefined functions were named correctly, not mentioned (gaps) or misunderstood (mistakes). In order to test the hypothesis, the additional insights and corrections of mistakes were therefore counted for each participant's explanation.

For H2, the transcribed data was examined on how often a participant verified an assumption during their analysis in which they have re-examined an issue – which will be referred to as *verification*. If the coder was uncertain, the eye tracking recordings often helped to clarify the participant's approach. A second coder reviewed all found *verifications*. When there were discrepancies between the two coders they discussed them and acquired consent. Analysis success in the first task (functional analysis) was determined by counting the correct mentioning of 9 predefined functions. For the second task (synthesis-driven analysis) success was determined by the questionnaire on the systems behavior. The participants could get 9 points for correct answers on the system's behavior. The variable in which we measure the *analysis success* of the participants is a 0-18 scale, by combining the 2 tasks.

In addition to the hypotheses, we have examined the verifications in more detail. The verification of assumptions during the analysis were additionally coded. The verification activities were coded on the correctness of the participants' understanding before and after the verification, based on the think aloud protocol. The verifications have been further been distinct in a *qualitive verification* (e.g. There is an electric drive or not; two parts have contact or not) and an *evaluation* of one's assumption (e.g. there is a force, but it is not strong enough to damage the part). Another distinction of the verifications was if the participant found *evidence for* the assumption or *evidence against* it.

The correlation was calculated with the Pearson Correlation Coefficient and the respective p-value.

3 Results

During the first task (functional analysis), 18 out of 24 subjects understood the system for the most part (<50 % correct mentioned functions; see also diagram 1).

The second task (synthesis-driven analysis) was much more difficult. Only 8 out of 24 subjects recognized the correct cause of the problem and were thus able to develop a suitable solution.

3.1 H1 A structured verbalization of one's own understanding of a technical system helps to identify gaps and mistakes in the own analysis.

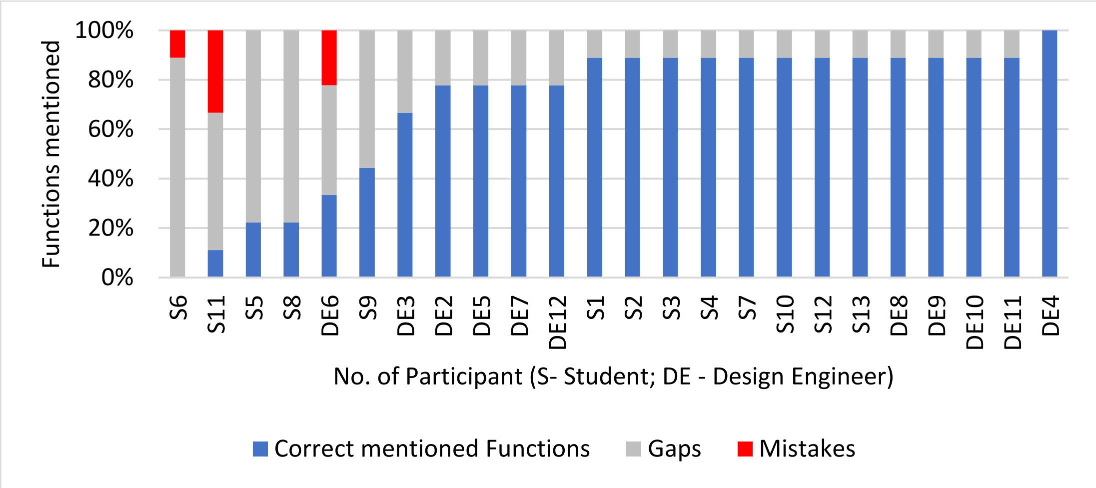
In order to be able to make a conclusion on this hypothesis, we have coded the participants' explanations after the first task (lawn sprinkler), in the categories *correct mentioned function/behavior*, *gaps* and *mistakes.*

3 of the participants had mistakes in their understanding of the system, even after the analysis and their verbalization. 6 participants had considerable gaps in their understanding of the system, they mentioned less than 50% of the predefined functions correct.

Nevertheless, none of the 24 participants identified a gap in their understanding during their verbalization. One participant (Student S11) identified one mistake while he verbalized his findings. He thought that the lawn sprinkler was driven by an electric drive. During his verbalization he realized, that there was no electric drive.

In sum, only one participant identified a mistake during the verbalization, and none identified a gap in their understanding of the system. Hypothesis 1 is therefore not supported by the results of this study.

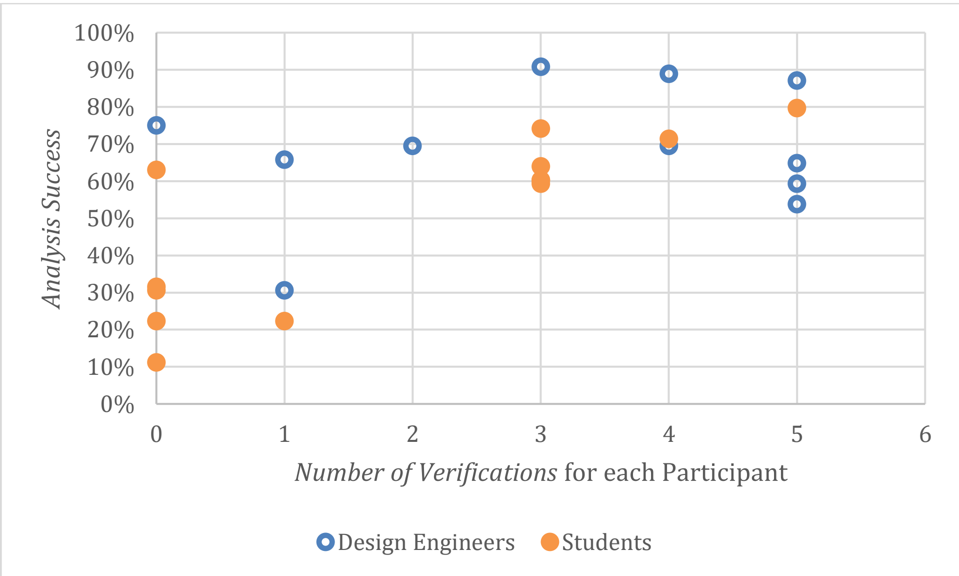
Diagram 1 Functions mentioned during the verbalization after Task 1 (lawn sprinkler)



3.2 H2 Verifying own assumptions about the function and behavior of a technical system improves the quality of the analysis.

Diagram 2 shows the number of verifications and the *analysis success* (combined for both tasks) for each participant. There is a correlation between the *number of verifications* and the *analysis success* (r=0.63 p=0.001, n=24).

Diagram 2 Analysis Success over the Number of Verifications per Participant



It appears that the *verifications* of the participants are related to the *analysis success*. Thus, Hypothesis 2 is supported.

3.3 Detailed examination of verifications

In total, the two coders identified 64 verifications of assumptions. In table 1 the change of the participants understanding of the system through the verifications is represented. The most verifications (45 out of 64) did not distinctly change the correctness of understanding. 15

verifications led to a better understanding and 4 verifications worsened the participants understanding.

Table 1. Classification of the verifications

Change of participants' understanding	Total number of verifications	Type of verification		Type of evidence	
		qualitative	evaluated	for the assumption	against the assumption
Improvements	15	13	2	5	10
no change	45	31	14	41	4
Worsening	4	3	1	2	2
		47	17	48	16
Total	64	64		64	

The table shows also that verification activities in which the participants found evidence against their assumptions have the highest rate to improve the correctness of understanding.
Considering only the high and low performing participants (the 5 participants with the highest/lowest score in the analysis) the data also show a strong correlation ($r=0.85$ $p=0.002$, $n=10$) between the amount of *evaluations* and the *analysis success*.

4 Discussion

This study investigated how design engineers und mechanical engineering students analyze mechanical systems. Our initial impression was confirmed in this study. Not verified assumptions during the analysis of technical systems often lead to errors in the analysis. If the design engineer understands content incorrectly, it often leads to iterations. We have therefore quantitatively examined how designers can ensure that their understanding of the analysis is correct.

4.1 H1 A structured verbalization of one's own understanding of a technical system helps to identify gaps and mistakes in the own analysis.

The structured verbalization of one's own understanding of a technical system seemed a promising possibility to identify gaps and mistakes in the analysis. In our preliminary study, 3 out of 4 students had additional findings as they stated their understanding of the system. Verbalizing one´s own understanding leads to identifying mistakes and gaps, which is stated in the literature (Hacker, 2002; Rosenblit & Keil, 2002). It is therefore surprising that out of the 24 subjects only one subject has detected a mistake in his understanding and none found a gap in his understanding of the system. We see two possible reasons for this. (1) Most subjects either understood the system very well or very poorly. The high performers understood almost everything and could not improve their understanding much. The low performers did only recognize single subfunctions and did not understand enough that their explanation could had helped. We suspect that the participants must have understood at least a general overview of the system to benefit from the explanation and there must be capacity for further insights. (2) In the instructions of the study, we asked the subjects to verbally communicate their findings to the moderator after the analysis. Rosenblit & Keil (2002) state that to overcome the illusion of explanatory depth one must detailed explain the phenomena with a step-by-step causal explanation. Our instructions could have been to indefinite to identify gaps and mistakes in the participants understanding of the system. But we cannot explain why 3 participants in the preliminary study benefited so much from the explanation and why we were unable to determine the effect in this study.

4.2 H2 Verifying own assumptions about the function and behavior of a technical system improves the quality of the analysis.

Some publications mentioned that verifying assumptions on a systems function and behavior enhances the completeness and correctness of the analysis. However, we have not found a quantitative study on this topic. This study presents the first quantitative data that shows a significant correlation ($r=0.63$ $p=0.001$, $n=24$) between the number of *verifications* and the *analysis success*. The results also show that in (a few) cases a verification can also lead to incorrect findings during the analysis. The positive effects of reviews are described at least qualitatively in the literature. We have not found any literature describing the possible negative consequences.

Further research is needed to identify the effects of these errors and how they can be avoided. Even though it is obvious, designers should be aware that verifying their assumptions leads to better analytical results.

4.3 Detailed examination of verifications

The 64 verifications had been subdivided on two attributes of verification (qualitative | evaluate) and the type of evidence (for the assumption | against the assumption). The most effective way to verify assumptions was evidence against assumptions. However, the participants mostly searched – and therefore found - evidence for their assumptions. Just because there is evidence to support this assumption does not mean that it has to be correct. Whereas evidence against an assumption is a clear sign that one's own assumption is wrong. As a result, the participants questioned their own understanding when they found evidence against their assumptions. In 10 out of 16 cases, they corrected their assumptions when evidence against an assumption was found.

The successful subjects (often the experienced ones) not only tested their assumptions qualitatively, but also evaluated their idea of whether they agree with reality (e.g. This component is subject to a load but is it strong enough to damage the part?). The positive effects can be shown when focusing on the high and low performing participants. For this group the data shows a strong correlation ($r=0.85$ $p=0.002$, $n=10$) between the amount of *evaluations* and the *analysis success*.

In sum, it could often be observed that verifying the assumptions led to a better understanding of the system. When verifying assumptions, the subjects found more details about the system. The advantage of verification is not only to determine whether one’s own understanding is wrong or correct, it often leads to a deeper understanding.

5 Conclusion

In this study we tested two hypotheses on how we can improve the qualified use of assumptions and therefore the analysis of design engineers. We did not find evidence that the verbalization of one's own understanding of a technical system helps to identify gaps and mistakes in the own analysis. We assume that it is necessary, that the participant has to explain the function very detailed and not only describe it.

We found evidence that verifying assumptions on a system’s function and behavior enhances the completeness and correctness of the analysis. Especially the deliberate questioning of one's own assumptions and the search for indices that are against one's own assumption are signs of a good analysis. The analysis does not have to be correct from the start, but when design

engineers start their synthesis they should be sure that their understanding of the system is correct. It seems to be helpful to make several assumptions and to choose the most likely explanation based on the available facts. A procedure that seems logical but was only used by very few participants. It is therefore necessary to create an awareness of typical mistakes and successful procedures during analysis among practitioners and students.
We will use the findings of this study to develop an analysis method to actively support the testing of assumptions. The utility and applicability of this method will be examined in an experiment.

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Citations and References

Booth, J. W., Reid, T. N., Eckert, C., & Ramani, K. (2015). Comparing functional analysis methods for product dissection tasks. Journal of Mechanical Design, 137(8), 081101.

Dylla, Norbert. Denk-und Handlungsabläufe beim Konstruieren. Diss. Technische Universität München, 1990.

Ehrlenspiel, K., & Meerkamm, H. (2013). Integrierte Produktentwicklung: Denkabläufe, Methodeneinsatz, Zusammenarbeit. Carl Hanser Verlag GmbH Co KG.

Hacker, W. (2002). Denken in der Produktentwicklung. vdf, Hochschulverl. an der ETH Zürich.

Hess, S., Lohmeyer, Q., & Meboldt, M. (2017). Utilization of Mobile Eye Tracking Data to Improve Engineering Design Education. In DS 88: Proceedings of the 19th International Conference on Engineering and Product Design Education (E&PDE17), Building Community: Design Education for a Sustainable Future, Oslo, Norway, 7 & 8 September 2017.

Matthiesen, S., & Nelius, T. (2018). EYE TRACKING STUDY ON SUCCESSFUL MICRO-STRATEGIES BY DESIGN ENGINEERS FOR THE SYNTHESIS-DRIVEN ANALYSIS OF TECHNICAL SYSTEMS. In TMCE 2018: Proceedings of TMCE 2018, 7-11 May 2018, Las Palmas de Gran Canaria, Spain.

Matthiesen, S., Nelius, T., Pflegler, B., & Gutmann, T. (2017). Studiendesign zur Untersuchung der synthesegetriebenen Analyse von Konstrukteuren. In DFX 2017: Proceedings of the 28th Symposium Design for X, 4-5 October 2017, Bamberg, Germany.

Meboldt, M., Matthiesen, S., & Lohmeyer, Q. (2013). The dilemma of managing iterations in time-to-market development processes. In Second International Workshop on the Modelling and Management of Engineering Processes (MMEP 2012). Eidgenössische Technische Hochschule Zürich.

Rozenblit, L., & Keil, F. (2002). The misunderstood limits of folk science: An illusion of explanatory depth. Cognitive science, 26(5), 521-562.

Ruckpaul, A., Kriltz, A., & Matthiesen, S. (2014). Using eye tracking to understand the engineering designers' behavior in synthesis-driven analyzing processes: experiences in study design. In International conference on human behavior in design HBiD.

Smith, R. P., & Tjandra, P. (1998). Experimental observation of iteration in engineering design. Research in Engineering Design, 10(2), 107-117.

Wynn, D. C., & Eckert, C. M. (2017). Perspectives on iteration in design and development. Research in Engineering Design, 28(2), 153-184.