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ESTIMATION AND ITS ROLE IN ENGINEERING DESIGN - AN INTRODUCTION

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ABSTRACT
Estimation is a relevant method for problem solving in product development due to the deficiencies in information availability and certainty, as well as because of short resources. Nevertheless, estimation as a method is hardly mentioned in literature on product development nor is it part of engineering education. As a consequence good performance in estimation and the development of estimation competence is left to chance, i.e. expected to be built up through experience. We believe that estimation can be supported and taught. Hence estimation competence can be developed purposive and more quickly.
The aims of the research introduced in this paper are to understand the relevance and functioning of estimation in engineering design, and to develop support for engineering practice and education based on this understanding. This paper focuses on demonstrating the relevance of the topic by addressing the following questions:
- Why is estimation important for engineering design?
- What is the state of the art in understanding of estimation in general?
- What is the state of the art of estimation as a method in engineering design?

We propose our research framework on the basis of this initial investigation. According to the goal, approach and scope of our research, the main research questions on estimation in engineering design that we wish to answer are formulated, as well as the research methods we use. Furthermore the first results on the characteristics of estimation in engineering design identified by tests, as well as by video and protocol analysis are summarized. At least, an outlook on the prospect research is given.

Keywords: Estimation, uncertainty, engineering education, design problem solving, decision making

1 INTRODUCTION
In many situations in our personal and professional lives we need to make an estimate, usually for the purpose of making a decision or improving our understanding. An estimate is acceptable because it provides useful information when a more detailed analysis is unnecessary, impractical or impossible because the situation does not provide enough time, information or other resources. In engineering, a broad variety of activities benefit from the use of estimation, including evaluating the feasibility or suitability of an idea in product development, planning projects or experiments, sizing and selecting materials or components and checking detailed analyses [1].
Particularly for problem solving in product development, estimation in its manifold form of appearance is assumed a relevant method due to deficiencies in information availability and certainty, as well because of short resources [1]. Engineers need to estimate if required information is not available in sufficient quality or quantity and if they do not want to merely guess. Nevertheless estimation as a method is scarcely mentioned among the great number of methods, methodologies, guidelines and tools that can be found to support the product development process in standard literature on product development (e.g. [2], [3], [4], [5]). Searching methods in engineering design with the keyword "estimation" does however lead to some results. Expert estimation is mentioned in the VDI guideline 2221 [6] as a quick way to evaluate solutions. Lindemann [7] proposes estimation as a method to analyse the properties of future products. However neither source provides details about these methods. Cost estimation is the only type of estimation in product development for which detailed support can be found in several sources (e.g. [2], [3]). A more detailed description of these methods and the current state of estimation in engineering design is given in Section 3.

The same situation can be found in engineering education: estimation methods other than those related to cost are not taught, neither is estimation explicitly supported in exercises nor the compilation and presentation of lecture contents. We observed how this situation caused our engineering design students great problems when they had to develop embodiment designs from principle sketches with the sufficient data given to them. Estimation plays an important role in this step, from an abstract and qualitative level to a concrete and quantitative one. Good performance in estimation and the development of estimation competence is left to chance, i.e. expected to be built up through experience.

We believe that estimation can be supported and taught. Hence estimation competence can be developed purposive and more quickly. The aims of the research introduced in this paper are to understand the relevance and functioning of estimation in engineering design, and to develop support for estimation in engineering practice and education based on this understanding. This paper focuses on demonstrating the relevance of the topic by addressing the following questions:

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2 UNDERSTANDING ESTIMATION

Estimation is a term used in many domains for very different activities and purposes. Especially in common speech, estimation covers a wide range of activities to determine values with some degree of uncertainty. According to the Oxford Advanced Learners Dictionary, an estimate is a "judgment or calculation of the approximate size, cost, value, etc. of something" [8]. In line with this definition, Figure 1 shows the range of estimation activities between "random guessing" and "detail calculation", which we consider to be part of estimation. Random guessing is not estimation because it does not involve judgement or calculation. Rough calculation is still estimation because it will result in an approximate size, cost, value, etc. Detail calculation is no longer considered to be estimation.

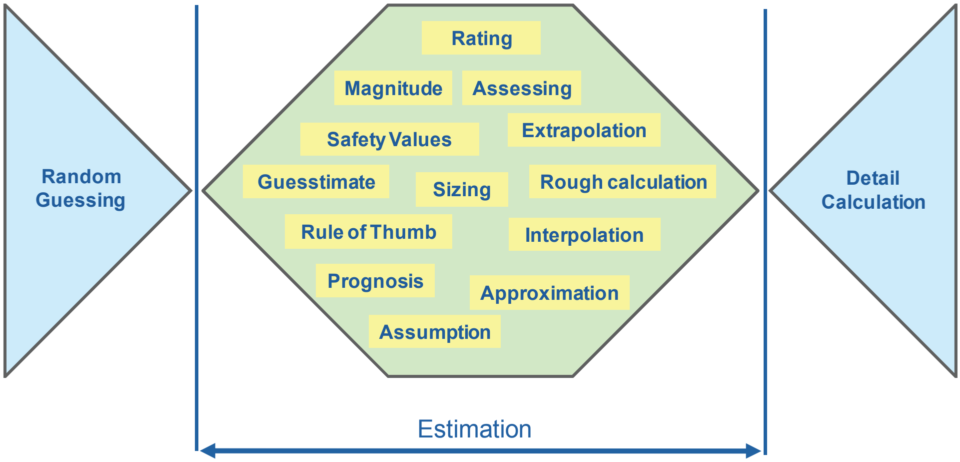

Figure 1: Range of estimation activities

The common purpose of all estimation activities is to find a basis for making a decision, in order to proceed in a problem solving process that is subject to a lack of information or methods to determine the next step with certainty. The degree of uncertainty can be either intentional or inevitable [9].

Resources such as time and budget might be too limited to wait for or search for more precise information or apply more detailed methods. More detailed information or methods might not exist or may be unknown. Efficiency considerations may lead to the decision not to acquire and analyse all available information, even if the necessary resources to do so would be available. Gathering more or more precise information could require a disproportionately high level of effort for the particular stage within the development process. Furthermore, the accuracy of results may not have to be very high at certain phases of the development process. As a consequence the decision achieved by estimating will always be afflicted with uncertainty [10].

According to [1] estimation is synonymous with analysis in the sense that all quantities are determined to some level of specificity. Specificity can be characterized by accuracy. Accuracy is a measure of how close a given solution is to the actual solution. Specificity can also be defined as the combination of resolution and certainty. Resolution and certainty are useful in a wider range of situations. The actual solutions to most quantity problems are either not known or not knowable, and by that accuracy is not definable. On the other hand, resolution and certainty apply to a solution regardless of whether or not an actual solution is knowable and still capture the notion of accuracy. A solution that is known to high resolution with certainty must be an accurate solution. An analysis that obtains higher specificity is generally less economical, i.e. it requires more resources in the form of time, information, formalization or computation. A rough estimate is an analysis that provides relatively low specificity with high economy. In practice, rough estimates are commonly referred to by several different names, including order-of-magnitude estimate, ballpark estimate, simple calculation, back-of-the-envelope calculation and rough guess. These names are often suggestive of the relative level of resources involved, the resolution desired or action to be taken [1].

Although estimation as an explicit method is not established in engineering design problem solving, estimation methods are applied in several other areas. In industry, estimation as an explicit method is most commonly used in project management and project planning for predicting the effort and cost of projects, for example in software development (e.g. [11]). In small trade a major field of application for estimation as an explicit method is the offer proposal preparation in the construction sector. By analogies it might be possible to use elements of these applied methods to develop the aspired support in engineering design.

Estimation as a scientific topic is considered much more in cognitive psychology and neurology than in engineering design (e.g. [12], [13]). The object of investigation in these areas is the human mental capability and estimation is used as an indicator for this. In many studies, the goal of research is the detection of consequences from brain injuries or mental disorders. In tests like the Cognitive Estimation Test (CET) the focus is put on apperception and cognition. These tests are useful to examine the capability of subjects to estimate neutral parameters, but they will not provide information about the specific characteristics of estimation in engineering design as a complex problem solving process. In cognitive and educational science, a number of studies have been conducted that ask people to give simple estimates for quantities. Most of these studies investigate basic quantities from everyday life, preferential with values on the human magnitude. These quantities include number, length, time, frequency, probability and percentage, as well as area, volume, weight, and temperature. The majority of studies involve pupils in elementary and middle school. Some studies examine high school and college students. Responses that subjects can give differ in the amount of information and corresponding actions they use to make an estimate. In almost all estimation studies, subjects simply provide an answer value directly. This quick question-answer process just indicates if people know values for certain quantities. Some studies focus on how reference values are used to make estimates. Covered by problem-solving research, instead of research on estimation directly, are situations in which subjects carry out extensive problem-solving activity in several steps using a considerable amount of information in order to determine values. A more detailed abridgement of estimation studies can be found in [1].

3 ESTIMATION IN ENGINEERING DESIGN

A broad variety of activities benefit from the use of estimation in engineering, including evaluating the feasibility or plausibility of an idea in product design, planning projects or experiments, sizing and selecting materials or components and checking detailed analyses [1]. According to Goguen [14] most of engineering, particularly design, can best be represented with some level of imprecision or

approximation: “Fuzziness is more than the exception in engineering design problems: usually there is no well-defined best solution or design.” In product development estimation is often used for prediction of aspects important for product planning, like forecasting cost, time or risk, but there is little evidence of estimation as a method in engineering design.
Based on the theory of problem solving as information processing [15], Bischof [16] has analysed the information flow through more than 200 different methods and guidelines currently used within the product development process. By classification of the required input and the delivered output of each method, favourable allocation to earlier or later phases of the product development process was possible, even though many methods could be used in several steps. His analysis has shown that most methods are for use in the early phases of the product development process, while there is only a small set of methods used for the later phases, which are mainly helpful for quality and calculating aspects only. Among all analyzed methods there was no useful support found for transforming principal solutions (concepts) into detailed solutions (preliminary and definitive layouts). Estimation plays an important role in this step from an abstract and qualitative level to a concrete and quantitative one.
Searching methods in engineering design with the keyword “estimation” does however lead to some results. VDI guideline 2221 [6] mentions the expert estimation as explained by Geschka and Reibnitz [17]. According to them, estimation can be used as a fast “systematic- intuitive” evaluation method hence the results should be checked using other evaluation procedures. Pre-formulated questions can help to improve the outcomes of this method. It is especially proposed for ill-structured problems and not used for generating new information, but the results of other methods can be checked for plausibility.
Lindemann [7] explains an estimation method in a different way. He proposes estimation as a method to analyse the properties of future products. According to him, it is a useful method to generate the required information when precise calculations, numerical simulations and physical tests cannot be carried out due to high costs or complexity. It is an engineering method and “more than a vague feeling”. Estimates can be based on experience or on comparisons with similar objects. Different ways to improve the estimates are recommended [7]:

- Dividing the estimation task in manageable smaller tasks may lead to better results.
- Estimates are better if more people are involved. Since knowledge and experience are necessary, it is useful if experts come together to work on one task.
- A combination of estimates and exact calculation will also lead to outcomes that are more precise. The more important factors should be calculated, while the less important ones can be estimated to accelerate the process.
- A fourth way to get better data out of the estimation method is using comparison with data of similar problems.
- Experience in the pertained topic as well as in estimation as a method has a big influence on the estimates. If the estimation method is frequently used, the probability of getting better results is higher. Therefore the results of former estimations have to be compared with precise data, in order to get a feedback on the quality of the estimates, and thus have a higher learning effect.

Even though the estimation method is faster, cheaper and can be run with less effort than calculations or tests, it has several disadvantages [7]:

- Estimates are less precise than calculations and tests.
- Recognized errors often cannot be used to improve the results of the estimation, to some extent it still remains a matter of “feeling”.
- Results are dependent on the people performing the estimation. They sometimes cannot be reconstructed by other people.
- If the estimator is no longer available there is no continuity in the results.
- In the short term it is impossible to learn estimation.

The expert estimation method described in [17] is a simplified evaluation method, asking experts for their opinion supported by a checklist or pre-formulated questions. Hence it is not applicable to generate a solution, and by this does not match our research focus as described in Section 4.
The recommendations given by Lindemann [7] are either directly transferred from the cost estimation measures proposed by Ehrlenspiel [4], or can be considered as simple “common sense”. Some are identical to general problem solving recommendations as described by Pahl & Beitz [3]. An empirical

foundation for the recommendations by own studies or sources in cognitive science is missing as well. A definition of "estimation competence" derived from Lindemann's description of estimation would be very similar to "expertise". Hence estimation only would be the application of expertise. Concerning the aspired support for education, the given statement about the ability to learn estimation is very vague and unhelpful.

This inventory of estimation as a method in engineering design enforces the appraisal, that research in this area is necessary. The framework of our research approach is introduced in the following section.

4 RESEARCH FRAMEWORK

Taking the expanse of the topic of 'estimation' into account, it is appropriate to focus on certain aspects Additionally, some issues are of major interest with regards to engineering design, in particular the core process as design problem solving for creation of a technical artefact. The different dimensions of this focus are described after research objectives, research approach and major research questions have been introduced.

4.1 Research Objectives

The overall goal is to raise the probability that engineers give good estimates. Therefore support for engineering practice and education should be developed. In particular a method for explicit, discursive estimation, enabling designers to give good estimates should be worked out. In addition proposals for an appropriate integration of estimation should be derived, regarding its importance and functioning in the systematic product development process. As a result of this advice for rethinking engineering education shall be given. This contains integration of estimation as a method, as well as adequate compilation and representation of all subject matter, regarding the requirements of developing estimation competence.

All this requires understanding of relevance and functionality of estimation in engineering design as a preliminary result.

4.2 Research Approach

According to Adelson [18] the complex behaviours required to solve engineering problems should be described by cognitive models at the level of the underlying process and its functional mechanisms. Each mechanism can transform classes of input into classes of output. The models also specify the interactions among the mechanisms. These models can generate explanations and predictions about the behaviours that constitute a skill. They also provide insights concerning support and teaching tools for practitioners.

Following the approach of Adelson, the first prerequisite for achievement of the aforementioned objectives is to understand the nature of estimation in general with the help of cognitive psychology. The major research method for this first part of descriptive study is literature research.

In addition to the general characteristics of estimation, specifics of estimation in solving complex technical problems have to be determined. Since cognitive science studies rarely examine estimation in the context of complex problems, own studies are inevitable. Video and protocol analysis using "think aloud" are the appropriate methods for answering this question.

Examining the relevance of estimation for progress in product development and the quality of its results by analyzing engineers design activities should lead to recommendations for systematic product development and the advancement of engineering education.

4.3 Research Questions

The research approach induces several main research questions:

- How is estimation working as a cognitive process?
- What are the specifics of estimation in solving complex technical problems?
- Where, how and for what is estimation used in engineering design?
- What are influencing factors on estimation ability and estimation results?
- Which of these influencing factors can be addressed by support?

These questions are only the main ones, each containing several research questions on a more detailed level. In answering the questions descriptive and prescriptive study should be covered, although descriptive study will take the main emphasis.

4.4 Research focus

Because of the described multifaceted meaning of “estimation” definition of scope is necessary, and the variation addressed in this paper has to be pointed out.

Focus 1: Product Development Process Phase

Estimation is used to transform principle solutions (concepts) into detail solutions (preliminary and definitive layout). It plays an important role in this step from an abstract and qualitative level to a concrete and quantitative one. Based on the main phases of systematic product development after Pahl & Beitz [2] and according to the findings of [16], described in Section 3, the first focus of research is put on the transition from conceptual to embodiment design. This decision is additionally supported by our experiences from education in engineering design exercises.

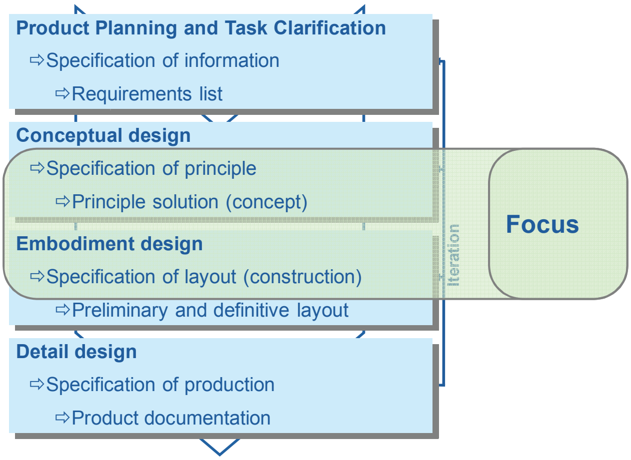

Figure 2: Research focus allocation to the design process phases by Pahl & Beitz

The aforementioned use of estimation for concretisation and quantification induces the second focus.

Focus 2: Quantitative estimation

Quantitative estimates, as defined for the research presented in this paper, do not necessarily contain a number or value. Rather a quantitative estimate is “aiming” for a quantity, for which giving a value is possible in general. Definitions of “estimate” in dictionaries meet this formulation without adding “quantitative”. In common speech, especially in German, “estimate” is often used for statements which are assumptions, suggestions or opinions. Quantity is used in this paper equally as physical or technical quantity. Examples for physical or technical quantities are power, force, mass, etc. A quantitative estimate can either be an absolute or relative estimate. Comparative statements like “I think we should make this larger/smaller than …”, are also considered to be quantitative estimation, as long as a physical or technical quantity is addressed.

Similar to the considerations on uncertainty in Section 2, causes for quantitative estimation in engineering design are [19]:

1. Exact quantification is not appropriate, because:
   - the effort exceeds the benefit,
   - exact values are not necessary,
   - data is imprecise or afflicted with failure due to measurement equipment or procedure.
2. Exact quantification is not possible, because:
   - data is not available,
   - the object of estimation does not exist jet,
   - resources , especially time, are short,
   - the object of estimation is too complex.

Focus 3: Generative estimation

"Generative estimation" is the mode of estimation to be logically addressed in engineering design. It is defined complement to "analytic estimation", which is the type of estimation common especially in everyday life, but also in various professional and research domains. Two variant estimation tasks on the same object should illustrate this determination:

1. A real funnel is given to a test person, who should estimate the diameter of its outlet.
2. A test person is asked to design a funnel with a flow rate of 50 litres per minute.

In the first example the test person is analysing an existing object. The second task necessitates the mental creation of a funnel with an appropriate outlet, maybe accompanied by the use of mathematical operations based on the understanding of the physical concept of flow rate. Although in both cases the required value is the diameter of the funnels outlet, the second task is obviously the more difficult one. Starting from an existing object seems to be more "comfortable" for cognition.

Design or designing is a creational process. A major feature of designing is the uncertainty afflicted, prospective determination of product characteristics, aiming at intended product properties [20]. Accordingly, the main characteristic of generative estimation is its deployment to determine values for quantities of objects which do not yet exist.

From this perspective, estimation is closely related to decision making. The task of generative estimation in design is to define a value for one quantity of an object, i.e. decide what value this quantity should have. In a simplified model of estimation, based on the common definitions of knowledge (e.g. [21]), memorized factual knowledge contains the reference values from which, by comparison, estimates are derived. The cognitive process of estimating by applying the factual knowledge is constrained by the procedural knowledge, as part of the engineer's estimation competence. Of course, external information which is available in the estimation situation can be used as well. The engineer bases his decision on one hand on factual knowledge, which contains references to adjust his estimate. On the other hand procedural knowledge in matters of applying this factual knowledge for defining values is required. Like a pre-test run with engineering design scientists has shown, the task of generating values for a quantity of an object by estimation is much harder than estimating a value for an existing object.

The above description of generative estimation in engineering design already contains an association with product properties, which is part of the fourth focus area.

Focus 4: Product related estimation

Within the aforementioned framework of generative estimation, many activities in engineering design or product development could be numbered. Especially in the early phases of product development most information is afflicted with uncertainty. This could be:

- process related information
- marketing related data about customers
- …

Hence, estimation is widely applied in project management for prognostication of various resources demand; especially time (e.g. [22]). Marketing and sales are trying to predict customer preferences or behaviour and market development (e.g. [23]). Product planning draws up scenarios about technological, political and social development (e.g. [24]). Environmental scientists try to estimate the impact of products and related technologies on the environment (e.g. [25]). Quality engineers want to foresee safety risks and the probability of fault occurrence (e.g. [26]). Etc.

This paper and the related research addresses engineering in the narrower sense as design problem solving for creation of technical devices. Hereafter estimation is used to determine values for physical quantities related to products, which can be called "product characteristics", according to the denotation of [20]. By addressing product related quantitative data the more discovered field of estimating process parameters is intentionally excluded.

5 FINDINGS AND RESULTS

Besides extensive literature study, tests in the form of questionnaires and video and protocol analysis of design meetings have brought some first insight into the nature of estimation. Here only a brief summary is given.

5.1 Education, experience and estimate accuracy - Test

The first addressed research question has been: "Who is good at estimation?" and in particular: "Are engineers better estimators than others, and how is technical understanding in different forms influencing the results?" For that the test was accomplished by four groups [n=67] with differing educational background and professional experience. Members of our chair and other researchers in engineering design were chosen as graduated engineering designers with some experience. Second year students represented low experienced engineering designers. As group of non-engineers with a good technical understanding, research associates in physics at the TU Berlin were tested. The fourth group at least consisted of people from different professions not related to engineering at all.

The test aims at the influencing factors on estimation results. Therefore nine everyday or at least well known objects were selected. The specific values asked for however, were mostly unfamiliar to the test persons. They differed in the range of size and the quantities of the values in their degree of abstractness.

Each candidate was given five minutes to estimate nine values, scaled from small to big in the three categories length (wall thickness of a PET bottle, racing bicycle, air craft carrier), mass (pen, book, car) and power (electric toothbrush, electric oven, bus). A more detailed description of the test can be found in [27].

The test indicated that engineering education and experience has got a substantial influence on the ability to give good estimations regarding technical quantities, even though not intentionally addressed. Summarized the findings have been:

1. Engineering designers can estimate technical factors more precisely than other people.
2. Graduate engineering designers can estimate technical factors better than undergraduate.
3. Having a technical understanding helps to estimate technical factors.
4. Medium sized factors are easier to estimate than exceptionally small or large ones.
5. Less abstract factors are easier to estimate than more abstract ones.

Although the test design was not appropriate for detail conclusions, we could already see that engineers have far better estimation abilities than non-technically educated persons. This finding leads to the question of how these abilities are gained and how this side effect of engineering education can be enforced and steered.

5.2 Group aspects of estimation - Video and protocol analysis

One influencing factor on estimation results is certainly the situation in which it is performed. The estimator can be supported or distracted by anything he perceives. In laboratory studies, these influences can be controlled or eliminated. In real life, engineers often work in teams. The colleagues can be a source for additional information or by interaction, change the process of estimation essentially. Therefore the first attempt of using video and protocol analysis to find out more about estimation behaviour of engineers has been combined with the question: Where, how and for what is estimation used in design teams?

The explorative, comparative protocol analysis focused on two meetings of a product development project recorded by the DTRS7 organisation (http://design.open.ac.uk/dtrs7) [28]. The two meetings addressed different problems - mechanical and electrical engineering - of the same product, and the participants of the two meetings varied slightly. The goal of both meetings was to use brainstorming to find solutions for the given design task. The analysis focused on the protocols. The videos were used to verify our interpretation of the statements in the protocols.

As to be expected, estimation in groups works differently due to the interaction of the group members. Even though the analyzed DTRS7 design sessions have not comprehensively covered the functionality of estimation in general, several additional roles of estimation, specific for groups, could be determined.

The individual use of estimation cannot be observed unambiguously, because subjects had not been instructed to "think aloud". Nevertheless in discussions estimation is used for various purposes. For the most part, subjects apply estimates to access ideas or proposals of other group members, e.g.: […] *It'll be about fifty percent more expensive.* […]. The ultimate goal of this is to promote the solution finding process by narrowing the solution space or choosing one particular track to follow up. For this,

ideas are elaborated or substantiated by estimation, to provide an opportunity for feasibility testing, verification or rejection and comparison of ideas.
Besides this, estimates are used to define requirements or constraints and to achieve a better understanding of the task, e.g.: […] *Size is dictated by cost. Really it needs to be quite narrow.* […].
In several cases, estimation is not directly used to enhance the information content, but to encourage discussion by open questions, or to involve more reserved group members by asking them to give an estimate. , e.g.: […] *Is there five hundred grams?* […].

Concerning research methodology it should be added, that video analysis is not the best way of examining estimation as a cognitive process. Individual observation using "think aloud" is a more fruitful method to study estimation behaviour and written tests are helpful to gather data on estimate's quality. In either case, larger samples would be helpful to abate the impact of individual differences of the subjects beside the influences according to engineering education and practical experience.

6 CONCLUDING REMARKS

The intent of research presented in this paper is to create awareness for estimation as a legitimate and important procedure in certain phases of the product development process and its significance in engineering practice and accordingly education.
The present state of descriptive research and prescriptive literature on estimation as a method in engineering design is insufficient. The major publication on estimation in engineering with focus on education by Linder, [1] proposes a framework for describing estimation, but his studies on estimation performance lead to the conclusion that the results are widely superposed by the deficient understanding of basic physical concepts. The expert estimation method described in [17] is a simplified evaluation method, asking experts for their opinion supported by a checklist or pre-formulated questions. Hence it is not applicable to generate a solution and by this does not match our research focus. The recommendations given by Lindemann [7] are either directly transferred from the cost estimation measures proposed by Ehrlenspiel [4], or can be considered as simple "common sense". Some are identical to general problem solving recommendations as described by Pahl & Beitz [3]. An empirical foundation for the recommendations by own studies or sources in cognitive science is missing as well. A definition of "estimation competence" derived from Lindemann's description of estimation would be very similar to "expertise". Hence estimation only would be the application of expertise. Concerning the aspired support for education, the given statement about the ability to learn estimation is very vague and unhelpful.
This inventory of estimation as a method in engineering design enforces the appraisal, that research in this area is necessary. The initial investigations already have brought a substantial narrowing of the research topic, and the first results of our research have shown that research methods have to be chosen carefully.

7 PROSPECTIVE

Concurrent to the descriptive study, focussing on certain aspects of estimation will be continued as part of the process of research clarification. New tests will be designed for further examinations, so the different influences on estimation abilities can be separated, and more detailed conclusions about the influence of education and practical experience can be drawn. In addition laboratory studies will be carried out, in which different groups are observed, to gain detailed understanding of the specific attributes of estimation in the context of engineering design. Set-up and tasks have to force test persons to use estimation. An evaluation about the way in which the type and duration of work experience affects the estimation performance would also be necessary. After completion of the descriptive study, support can be derived by analysis of the influencing factors on estimation competence. This prescriptive study should cover industrial practice as well as education. Evaluation of the developed support should be the final step, hopefully feasible within the given time frame.

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