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SCHOOL CULTURE THROUGH PRAXIS

Michael VIELHABER, Fabio DOHR and Tobias LUEDEKE
Saarland University, Saarbruecken, Germany

ABSTRACT
From the beginnings of design methodology, the way how to teach and to learn engineering design has been controversially discussed. "School culture" and "shop culture" are terms representing this discussion, the first describing a more systematic view, the second describing a more problem-oriented "learning by doing" approach.
This paper originates from German design education. It presents an attempt to bring both sides closer together by teaching "school culture" knowledge through practical experience. For this purpose, a practical course was set up to achieve "learning design methodology by doing": Based on own practical design tasks, the students are guided to reflect their approach against a theoretical design methodology. As a result, this methodology is deeply inherited by the students, but also a basis is provided to rethink and potentially rework the theoretical framework, thereby helping to make it better suitable to and acceptable for engineering design practice, finally.
Regarding the VDI 2221 design methodology, main findings concern the importance of the initial phases, the transition from functional to geometric design, the point of time when conceptual design decisions are made, and the level of maturity of conceptual ideas evaluated in the decision process.

Keywords: Design methodology, design praxis, school & shop culture

1 OBJECTIVES

Since the first appearances of scientific design methodology around 1850, the way how to teach and to learn engineering design has been controversially discussed [1]. "School culture" and "shop culture" are terms representing this discussion, the first describing a more systematic view favoured mainly in Central European countries, the second describing a more problem-oriented "learning by doing" approach followed mainly in Anglo-American countries [2].
This paper originates from German design education. It describes an attempt to bring both sides closer together by teaching "school culture" knowledge through practical experience.

2 APPROACH

In German design education, engineering design methodology is generally taught following academic process frameworks such as the guideline VDI 2221 [3], although discrepancies of these frameworks with design practice are well known (e. g. [4]). This lecture-style education may be accompanied by tutorials in which students execute design projects following the methodology taught, and applying the methods and tools presented.
The authors have now set up a practical course in an attempt to bring theory and practice closer together and thereby to intensify the students' learning experience. The basic idea is to reverse the traditional learning order of "theory, then execute" in order to achieve "learning design methodology by doing": After giving a condensed input about the methodology suggested to be followed and the respective next process step, the students are asked to work on an own practical design task. Imitating a real customer situation, only rough requirements are provided to the students, who are asked to develop a comprehensive requirement specification themselves, first.
The different approaches followed are closely observed. Then, after each process step, its execution and results are reflected by the students not only from their project's point of view, but also and especially from a methodical one. Approaches of different student groups are compared, advantages and disadvantages of different proceedings discussed and then, at the end, mirrored with theoretical concepts behind the respective process step.

At the end of the project, the physical design results are undertaken an in-depth design review, and weaknesses are identified. Then, reasons for these weaknesses are sought for especially in the area of the methodology applied. Questions discussed include:

- Which steps of the methodology have been exactly followed? Which ones not, and why?
- Which steps have not been followed seriously enough or not in sufficient detail? What have been the consequences?
- Which steps have been followed but failed to achieve their intended results, and why?

Thus, advantages and disadvantages of each process step as well as the overall process flow are discussed and reviewed, and potentials for improvement are identified. To further support the discussion results and to achieve overall process feedback, a questionnaire was provided to the students at the end of the class. Questions of the questionnaire include:

- What has been the estimated effort for each process step?
- When was the first decision on a solution concept made?
- How often and when has this concept decision been revised?
- How helpful was the methodology provided?
- What could be potential improvements for that methodology?

For each class, one specific design methodology is chosen and the students are guided and encouraged to closely follow the high level process order for their team design project. In the first cycle, VDI 2221 was selected as a widely-used framework in German design education. Its process scope has been extended to cover prototype manufacturing through conventional or rapid prototyping technologies.

The project task has been to design a mechatronic bicycle brake with antilock and speed limiter function to be integrated into an existing electrical tricycle. This topic was selected by intention as a quite ambitious task with new design character, for which no industrialized solutions exist, yet.

In follow up classes, other methodologies will be taken as a basis; VDI 2206 [5] and a "Lean Product Development"-based framework [6] being the next examples.

Besides offering the students the opportunity to acquire design methodology themselves on their practical example, the presented approach also offers valuable scientific results. Advantages and disadvantages of the methodologies are worked out and made obvious on practical examples. Findings regarding different design methodologies can be brought together and compared. Finally, conclusions for a practice-oriented rework of the design methodologies can be derived.

3 RESULTS

The results are manifold and have been derived from both the analysis of the design results and the methodical discussions with the students as well as the questionnaires.

3.1 Design results

Out of the five participating project groups, the results of three exemplary ones will be described in the following, giving characteristic representations for the different approaches taken in the class.

The ***first group*** was tasked with optimizing a mechanical brake system. The students in this group followed a hands-on approach. The suggested process steps according to VDI 2221 were superficially followed, but concepts were discussed and found through side processes. Along the project, the solution approach changed several times, until finally a solution was realized that modified an existing patent, see figure 1. The solution proved to partially fulfil the requirements specified: the interlock function was addressed in detail, but the speed limiter function only on conceptual level.

This group can be taken as an example for designers not accepting the process model provided by VDI 2221. Concept decisions have been taken early, intuitively and not founded on a sound knowledge basis and evaluation process. A functional design step has not been done seriously. As a result, changes even on a conceptual level had to be executed up to the late process phases.

The ***second group*** was tasked with optimizing a hydraulic disc brake. The students stuck close to the suggested VDI 2221 process. Based on a thorough analysis, specification and functional design phase, an electromagnetic solution concept was chosen, detailed and finally realized, see figure 2. Only late in the detailing phase, it was discovered that physical limitations forced the design to be too heavy and too energy-consuming to be applicable on a bicycle level.

Although this group's concept was sound, its realization did not fulfil the requirements sufficiently. This may be disappointing; reviewing this group's approach however gives valuable hints regarding weaknesses of the theoretical framework followed, see chapter 3.2.

The ***third group*** was tasked with optimizing a hydraulic rim brake. The students also had basic design methodology knowledge, but they stuck to the suggested VDI 2221 methodology less closely. They put great focus on the specification phase, in which they also extensively analyzed market concepts and patents. The group showed less ambition in functional design and abstract creativity techniques (e.g. TRIZ), however made a sound concept selection which finally proved to deliver a working prototype – still too heavy, but with room for improvement, see figure 3.

In comparison, this group's result was successful; reviewing the group's approach also gives valuable hints regarding valuability and practicability of the suggested process steps of the VDI 2221 framework.

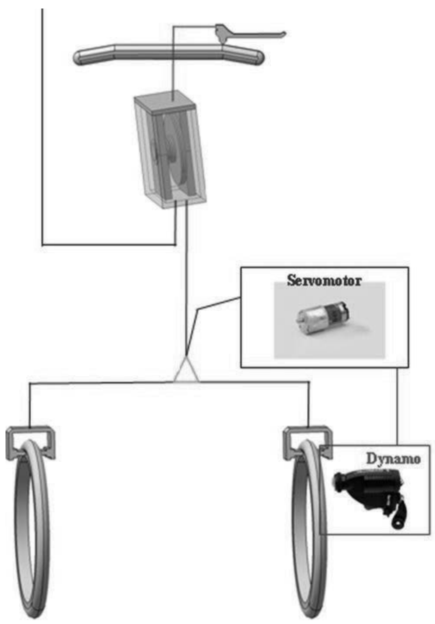

Figure 1.
Mechanical brake system (concept)

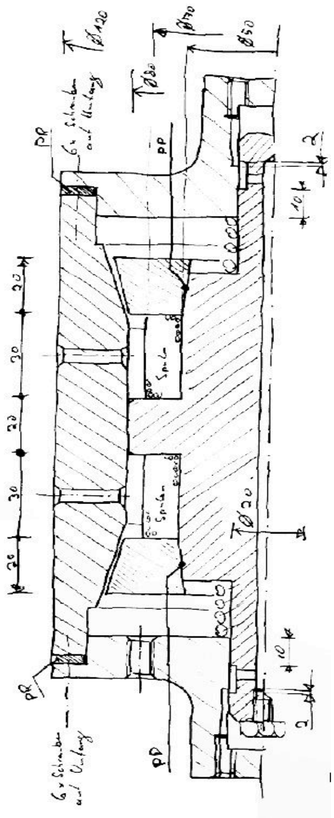

Figure 2.
Hydraulic disk brake (actuator only)

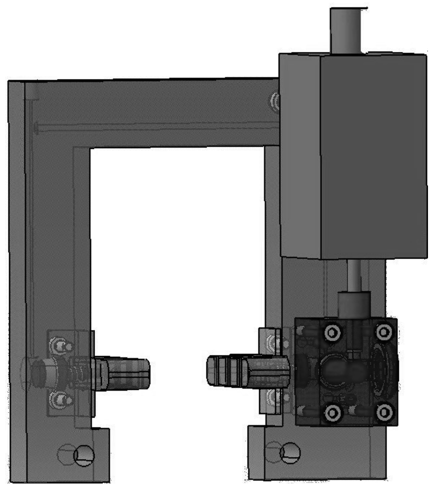

Figure 3.
Hydraulic rim brake

3.2 Discussion results

The entire practical class has been accompanied by intense discussions, which compared each step executed with the theoretical framework suggested to be followed. Through these discussions, the students were encouraged to reflect their own approach, inherit the theoretical process model, and build their own understanding about the process steps executed and methods applied.

From these discussions, it has also been possible to generalize the findings towards conclusions regarding the process model applied, i. e. the VDI 2221 framework. Although the sample was not large enough to be statistically valid, these findings can be helpful in order to further develop the design methodology followed to get better applicable and accepted in practice.

Regarding VDI 2221, main findings concern:

- the importance of the initial process phases
- difficulties in integrating functional design into the process flow
- the decision point for a conceptual solution
- the level of maturity of conceptual ideas evaluated in the decision process.

3.2.1 Initial process phases

Comparing the design results it got obvious that thorough product planning (including market and patent analysis) and requirements specification phases are essential preconditions for achieving good design results. The importance of the quality of the requirement specification, which is abstract to emphasize on a theoretical lecture level, only, can be directly experienced on the success of the design projects. E. g., the first group did not come to a sufficient requirements specification till the end of the project. The second group omitted important requirements such as the total weight and energy consumption, leading to a design solution working in principle, but not in practice in the target environment. The third group, which put special emphasis on product planning and specification, resulted in the best design result with the least design changes throughout the process.

3.2.2 Functional design

Functional design is an important, however abstract process step emphasized in various methodologies and lectures on design methodology in order to find unprecedented solution concepts on a functional level. In practice, this step appeared to be difficult to comprehend and to be really integrated into the process in between the specification and the geometry phase. It appeared especially difficult to concretize from the abstract functional to the geometric level.

However, the design results do not show a clear correlation between the effort put on functional design and the solution quality. Both the group with the most elaborated functional model (group 2) and the one with the hands-on approach (group 1) failed in the realization, whereas the in-between approach of group 3 led to the best result.

For further developing the design methodology of VDI 2221, one aspect could however be to focus on a better process integration of the functional design phase.

3.2.3 Decision point

Looking at the design approaches followed in the class, students tended to decide quite early on a concept to be worked out. Sometimes, this decision seems already taken even before the requirements specification is finished.

Looking at the design results, problems resulting from these too-early decision points get quite obvious: Design changes even on a basic conceptual level have been rather the rule than the exception. One reason for this phenomenon can be seen in the VDI 2221 process model: it requests a concept selection soon after the functional and before the detailing phase. For groups 1 and 2, such early decisions resulted in failed designs because of – in retrospect – wrong concept decisions.

3.2.4 Maturity of concepts

Closely linked to the earliness of the decision point is the maturity of concepts, on which decisions are made. VDI 2221 filters solution principles towards one selected concept, first, and works out this concept, afterwards. Other methodologies such as Lean Product Development postpone decisions on solution concepts until these are sufficiently detailed to be thoroughly evaluated [6].

Again, the results of both group 1 and group 2 show the negative impact of such decisions on an immature basis.

3.3 Questionnaire results

Finishing the course, the students were asked to complete a questionnaire to reflect the advantages and disadvantages of the methodology applied. Regarding the number of changes, the concepts have been revised up to three times, with the first group having the most revisions. Those groups which had more than one concept revision did the final revision during the late detailing phase due to problems regarding dimensioning or manufacturability.

Concerning the assistance of the methodology, most of the students appreciated to use it until the design phase. From this phase on the methodology did not deliver any concrete guidance anymore.

Although the course already focused on early phases, students indicated more intensive activities in early phases to be desirable. Nevertheless, turning the concept into a physical prototype required the most effort. Interestingly, the first group – which changed the concept three times in later phases – recommended less effort in early phases.

In total, students benefited from the structured procedure offered by the methodology and the possibility to assign tasks according to individual skills.

4 CONCLUSION

The target of the class had been to bring school and shop culture in engineering design closer together by teaching school culture indirectly – through practical experience. This target seems to have been reached quite successfully.

Discussions with the students have shown a deep understanding of the process model and of each process step with its advantages, disadvantages and pitfalls. Furthermore, this knowledge has not only been acquired theoretically, but critically reflected and thereby deeply inherited through successful or even unsuccessful realizations in practical designs.

This positive impression is independent of the design results as such, which only partially showed successful solutions, mainly due to the complexity of the design task. In fact, especially the failed concepts gave valuable hints regarding the methodology to be followed.

As an important side effect, valuable conclusions could be drawn regarding the applicability and improvement potentials of the intended VDI 2221 methodology. It is clear that results from a handful of design teams do not deliver statistically valid results; the insights gained however offer valuable starting points for further investigations and then, potentially, adaptions to the methodology followed. Figure 4 summarizes the main findings.

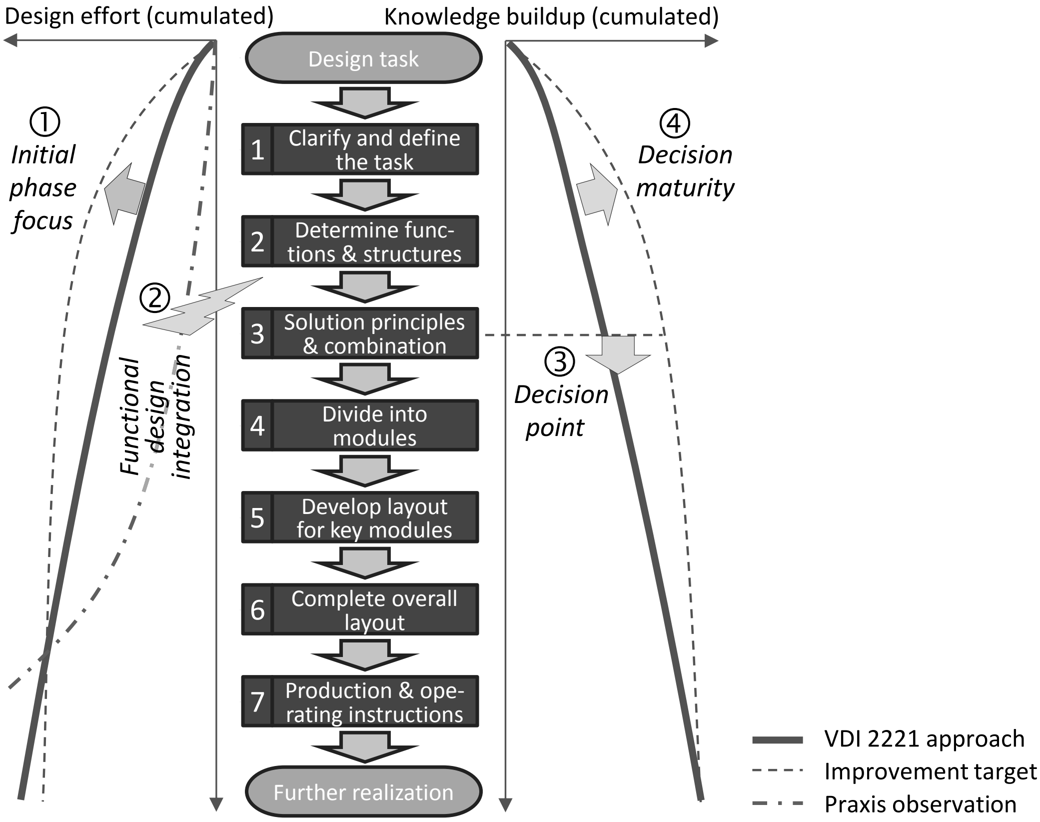

Figure 4. Conclusions regarding VDI 2221

1. ***Initial phase focus***: The known assumption, that efforts in the early phases of task clarification and specification pays off, is clearly supported by the design results. This point is already stressed by the VDI 2221 process model. Whereas design praxis often even cuts on this effort, the endeavour should be to support and systemize this effort through suitable and potentially adapted design methods.
2. ***Functional design integration***: Due to its character, functional design is more prevalent in school culture methodologies such as VDI 2221 than in more hands-on approaches such as the American approach of Ulrich and Eppinger [7].

   For students, its application seems difficult; the benefit of this abstraction step seems not directly obvious. Functional design is therefore often not executed seriously, or the results are not taken over to the solution finding phase. In this class, design results have not consistently shown significant benefits of intense functional modelling; this point would however need deeper validation. To better promote the application of functional design, design methodologies should focus on a clear integration of the functional steps into the process through applicable abstraction and concretization methods.

3. ***Decision point***: The student projects have clearly shown the danger of too early concept decisions; sometimes basic decisions are already made early in the specification phase. VDI 2221 sets this decision point soon after the abstract functional phase. At this point in the process, design knowledge may not be built up enough, yet, to support a sound concept selection. Focus should therefore be to keep concept decisions open and postpone them until they are supported by a sufficient knowledge level.
4. ***Decision maturity***: Closely linked to the previous point, the methodology should support early detailing and validation of concepts so that a higher maturity level is reached before conceptual decisions are made. It should therefore incorporate methods into the early process steps which support frontloading the knowledge build-up, e. g. functional modelling and simulation techniques.

Comparing the design task with the methodology applied, two additional aspects caught the authors' eyes.

First, the findings above appear similar to investigation results on differences between traditional design methodologies and knowledge-oriented Lean Product Development [6]. E. g., decision points and decision maturity are topics addressed through the set-based engineering approach of Lean Product Development. To validate this impression, one of the next praxis classes will therefore encourage its students to follow a Lean Product Development approach for their project.

Second, this class applied the traditional mechanics-oriented VDI 2221 process model on an innovative mechatronic product idea. Some of the student groups underestimated the electrical part in their designs, leading e. g. to the energy-consuming design solution of group 2 described above. In another praxis class, the mechatronics-oriented VDI 2206 methodology will therefore be used as a process model.

In summary, the approach described leads to a valuable learning experience for the students, and it offers clear hints for further developing and improving the design methodology followed, as well, thereby helping to make it better suitable to and acceptable by engineering design practice, finally.

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